Definition of Detection and Reaction Boundaries for Autonomous Marine Vessels

by

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Abstract

Definition of Detection and Reaction Boundaries for Autonomous Marine Vessels investigates the possibility of using a time-based self-separation method for safely navigating a controlled vessel with oncoming vessels and obstacles, which may or may not adhere to the appropriate guidelines for encounter navigation with another vessel. The simulation uses a validated model of a test vessel in order to accurately describe vessel dynamics when operating at a given desired speed, with an identical oncoming vessel. The simulation is used to calculate the last possible time before a collision would occur that the controlled vessel must begin manoeuvring in order to maintain a desired amount of separation with the intruder, regardless of whether the vessel is navigating properly or not. The algorithm was also tested in varying environmental conditions through a Monte Carlo simulation in order to confirm the results in non-calm water situations.

All results presented are with both the controlled vessel and intruding vessel travelling at 10 knots with a fixed maximum turn rate. There is a desired separation boundary of twice the length of the vessel from the centre point of the vessel, in all directions. The effects of changing the speed and size of the separation boundary were analyzed, and it was found that increasing the size of the separation boundary results in the vessel requiring more time to manoeuvre, while increasing the speed decreases the time required. Each of these relations between the time required to safely manoeuvre and the changing parameters are approximately linear. From the simulations, it was determined that the test vessel in a head-on encounter scenario must begin manoeuvring approximately 3 minutes with a non-compliant intruder and slightly more than 2 minutes for a compliant intruder. For a crossing scenario, the controlled vessel must begin to manoeuvre at least approximately 8 minutes prior to the closest point of approach for the intruder in order to maintain the desired separation. Lastly, for an

overtaking scenario, with the intruder travelling at 80% of the speed of the controlled vessel, the controlled vessel must begin to manoeuvre once again, approximately 8 minutes prior to the closest point of approach. Note that in certain environmental conditions, more time may be required to manoeuvre effectively.

Lay summary

The research undertaken can be used to advise regulatory establishment and explore a potential method for calculating the time required for autonomous vessels to be able to avoid other vessels while at sea. These results are important because they provide insight into ship design, sensor selection and the level of supervision that may be required for autonomous vessels. This was completed by running simulations with a modelled test vessel in order to find the last possible moment that the vessel must begin turning in order to avoid an oncoming vessel, whether or not that vessel will be manoeuvring appropriately according to the universally accepted "rules of the sea". The simulation was completed for all potential encounter angles in order to understand which encounter geometries may require more time to manoeuvre. An analysis into the effects of changing the speeds of the vessels and how far the vessel should remain from the oncoming vessel was also performed. For the general set of results, both vessels were travelling at 10 knots with a fixed maximum turn rate, with a desired safety boundary of twice the length of the vessel from the centre point. When the speed was increased, the time required to manoeuvre safely decreased, while when the size of the safety boundary increased, the time required to safely manoeuvre also increased. The inverse was also true for both parameters. When the oncoming vessel is approaching from either a crossing or overtaking angle, the controlled vessel should begin turning approximately 8 minutes prior to the point where it would collide with the oncoming vessel. For the head-on encounters, if the intruding vessel will also manoeuvre, the controlled vessel must begin turning slightly more than 2 minutes prior to the collision points, while if the intruding vessel will not manoeuvre, the controlled vessel requires approximately 3 minutes of manoeuvring time to safely avoid the intruder. When subject to environmental conditions, an additional safety factor should be applied in order to cover the adverse effects of the weather.

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List of abbreviations

ASV	Autonomous Surface Vessel
COLREG	International Regulations for Preventing Collisions at Sea
JARUS	Joint Authorities for Rule-making on Unmanned Systems
MASS	Maritime Autonomous Surface Ships
MIT	Massachusetts Institute of Technology
NASA	National Aeronautics and Space Administration
NRC	National Research Council Canada
PID	Proportional-Integral-Derivative
RTCA	Radio Technical Commission for Aeronautics
SORA	Specific Operations Risk Assessment

Chapter 1

Introduction

1.1 Background

At the present time, there is a focus on the safe adoption and operation of autonomous surface vessels (ASVs) in Canadian waters and elsewhere throughout the world. In order to ensure the safe implementation of these technologies, the formal definition of detection and reaction boundaries to ensure a safe distance is maintained between vessels is crucial because autonomous systems require a quantitative definition for their design and operation. The goal of this project is to help establish a set of guidelines with respect to how these operating boundaries are defined, which are important for the development of safe autonomous navigation technologies.

The concept for operating boundaries used for this project have been adapted from work previously completed in the aerospace field for detect and avoid in unmanned aircraft, for example the Radio Technical Commission for Aeronautics (RTCA) SC-228 and Joint Authorities for Rule-making on Unmanned Systems (JARUS) Specific Operations Risk Assessment (SORA) committees [1]. This approach involves defining three distinct regions for the ASV to monitor and avoid intruders. Outermost is a region where the ASV detects that there is an intruder nearby, however, it is outside the range of required avoidance manoeuvring. This would be known as the "detection region". Next, a region whereby the controlled ASV still has sufficient room to manoeuvre to avoid violating the collision boundary, but must actively avoid the oncoming intruder. This region is the "manoeuvring region". Lastly, the region withing the collision boundary, is considered unsafe due to the intruder in close proximity creating a high risk of collision. This is the "collision region".

In order to apply a similar approach to surface vessels that has been used for aircraft, the primary consideration is the lack of change in altitude in the surface vessel case. This applies to the avoidance manoeuvres performed, since the vessels are unable to change their altitude in order to avoid one another. The other consideration is the degrees of motion available to each case. In aircraft, all 6 degrees of freedom must be considered, while for surface vessels, only surge, sway and yaw must be accounted for. Lastly, surface vessels travel much slower than aircraft, and also take longer to perform a turn.

The concept presented in this thesis is that the alerting boundary which signifies that manoeuvring is required can be set based on the size and speed of the controlled ASV, allowing for a generalized set of parameters than can apply to a wide array of vessels. By implementing proper collision avoidance guidelines established by the International Regulations for Preventing Collisions at Sea (COLREGs) and the Canadian Collision Regulations, encounters can be modelled in an effort to determine reasonable guidelines for the size of these operating boundaries [2] [3]. All simulations to be completed in this thesis involve the use of a physically verified model from National Research Council Canada (NRC) to ensure the validity of the scenarios [4].

1.2 Problem Statement

The problem is to quantitatively define operating boundaries for surface vessels such that they have sufficient time to manoeuvre in order to avoid a collision once an intruder enters the purview of the vessel.

1.3 Technical Challenges

Technical challenges that occurred throughout the completion of this work are:

1. Developing an accurate vessel model for the simulation
2. Developing the algorithm to determine the time required for the vessel to safely manoeuvre
3. Accurately modelling the effects of the wind and surface currents on the vessel
4. Tuning the path following and surge controllers to precisely control the vessel during both calm water and non-calm water situations

Chapter 2

Literature Review and Related Work

2.1 History of Collision Regulations

The earliest mention of ships in recorded history dates back to approximately 2500BC in Egypt [5]. As long as there has been traffic in waterways, conventions must be adopted so that ships may behave in a predictable manner in order to avoid collisions with oncoming vessels. Originally, this would have been limited to small geographic regions, when vessels only covered a small distance. However, as the distance vessels travelled increased, the common set of conventions that all vessels must follow in order to ensure safe passage my be established. The common need for a set of collision avoidance guidelines was the impetus for the creation of the Steam Navigation Act, 1846, in order to ensure that vessels acting around the United Kingdom behaved in a predictable fashion [6].

The modern attempt at standardizing the behaviour of vessels when encountering an oncoming vessel are the COLREGs, established in 1972 and are currently the most up-to-date convention for manoeuvring [3]. The COLREGs outlined how vessels should behave when encountering another vessel at various orientations. This set of guidelines were also formally adopted by various countries, including by Canada through Transport Canada by establishing the Collision Regulations [2].

With the progression of technology towards the adoption of ASVs, the guidelines set out by the COLREGs are insufficiently detailed for the safe implementation of ASV collision avoidance requirements. The COLREGs focus on collision avoidance is largely qualitative, meant to be exercised by humans controlling a vessel [3]. See the manoeuvres defined by the COLREGs in Table 2.1. In order to allow for the adoption of ASVs, there must be a quantitative definition of when and how vessels should avoid each other when approaching. The absence of this quantitative definition demonstrates the necessity of this project for the implementation of collision avoidance systems for ASVs.

Encounter Geometry	Required Manoeuvre
Head-On	Both Vessels turn to starboard
Crossing	Vessel approaching the other vessel's port side turns to starboard
Overtaking	Overtaking vessel turns to starboard

Table 2.1: Proper manoeuvre to be undertaken by vessels for any encounter scenario

At the present time, work involving the implementation of collision avoidance for ASVs has adopted an estimated required boundary size for the operating regions. An example of this approach is in Almeida's work, whereby boundaries are defined for the operating regions, however, there is no justification provided for the size of the operating boundaries used [7]. This may result in overly conservative collision avoidance encounters, or the defined boundaries may not be large enough. The quantitative definition of these boundaries based on the manoeuvring capabilities of a vessel will help provide insight about the appropriate definition of these operating boundaries.

2.2 Background Theory and Methods

When considering the approach in simulation to assess the performance of the ASV when subjected to a collision avoidance scenario, ensuring that the modelling approach taken for the ASV accurately depicts the performance of the physical test vessel is critical to validating the results of the simulation. The simulation approach taken should ensure that the encounter scenarios are exhaustively analyzed to provide the correct results and conclusions. This simulation approach will include the impact of environmental effects, that the physical ASV may experience while in a collision avoidance situation. Overall, the direction of the project aligns well with work in the field working towards improving safety currently being undertaken at other institutions [8].

2.2.1 Modelling Approach

There are multiple approaches that can be taken to modelling a marine vessel, including various combinations of modelling motion of the six degrees of freedom: surge, sway, yaw, heave, pitch and roll to represent the movement of the vessel. For the application of collision avoidance, the relevant domain to consider is the horizontal motion of the vessel on the ocean surface plane. Horizontal motion is represented by the combination of surge, sway and yaw [9]. Assuming the presence of starboard-port symmetry, the surge will be decoupled from the yaw-sway aspects of the motion, and therefore can be considered separately [9].

The vessel heading in combination with the known initial position and speed will result in the position being updated at the desired simulation frequency by integrating the path along the orientation of the vessel. The yaw rate model can be obtained from physical model test data involving the model test vessel with system identification techniques, such as the approach outlined in [10]. This approach involves utilizing test data gathered from the model vessel in a state of varying input excitation in order to use statistical methods to regress on mathematical model parameters accurately describe the capabilities of the vessel to manoeuvre when subjected to a certain set of operating parameters [11]. When operating within the predefined operating bounds for the model, the behaviour of the test vessel for yaw-sway dynamics can be accurately depicted by modelling through system identification techniques. The surge modelling component can also be obtained from a similar approach.

Alternatively, the vessel dynamics can be modelled through the effects of the forces acting on the vessel, including hydrodynamic, propulsion, rudder, water resistance, wind and current. Using the known physical quantities of the test ship, the forces can be approximated and used to determine the acceleration of the vessel. Using the approach outlined by Clarke, the effects of hydrodynamic forces and the rudder force on the vessel can be modelled using the dimensions of the vessel and its rudder [12]. The propulsion force is the input used to control the surge of the vessel. Water resistance is dependent on the density of the water, the speed of the vessel and its physical properties. Lastly, the environmental forces depend on the physical dimensions of the vessel.

The forces and corresponding moments of the wind and current as they are applied to the ship is modelled through a transverse strip method in conjunction with the application of Morrison's equation [13] [14]. To do this, the ship was divided into multiple smaller sections both above and below the waterline in order to approximate the exposed surface area of the ship in both the axial and normal directions to the flow of current and wind. The sum of the forces applied to the axial component of the ship contribute to the surge, while the sum of the forces on the transverse strips into which the ship is subdivided are applied to the sway. Given that the sway forces are applied at various distances from the centre of the ship, a corresponding moment is also generated.

2.2.2 Simulation Approach

When completing a simulation to analyze the performance of a test vessel in collision avoidance scenarios, it is critical to be aware of the performance of the vessel for the given boundary conditions when the intruder approaches from a variety of angles, in a variety of different environmental states. Given that each of these can vary over a range, and the fact that it is unlikely that the worst case scenario would occur with an undesirable encounter geometry combined with historic extreme environmental disturbance, the absolute worst case outcome may never occur [15]. A method used to statistically analyze the potential outcomes is the Monte Carlo method, whereby the simulation variables such as the encounter angle and wind speed are modelled as independent random variables [16] [17]. By running the simulation over a large number of encounters with repeated unbiased sampling of the random variables, the expected range of outcomes will become apparent.

A study conducted on marine traffic data in the Gulf of Finland concluded that the likeliest encounter scenario to result in a collision is the overtaking encounter, followed by crossing scenarios and the least likelihood of collision being a head-on encounter [18]. As a result, these specific encounter geometries will be the focus of a Monte Carlo simulation to determine the range of potential outcomes for different weather conditions.

2.2.3 Collision Avoidance Approach

The method was adapted from a collision avoidance approach used in aircraft, developed by Massachusetts Institute of Technology's (MIT) Lincoln Laboratory and National Aeronautics and Space Administration (NASA) [19] [20]. This approach uses the relative velocity and displacement between the vessels in order to determine the time to closest point of approach. This time to closest point of approach in combination with a pre-defined separation boundary is used for the alerting logic to begin an evasive manoeuvre. The approach for alerting to be used for collision avoidance has been adapted to the marine surface space in a previous work [21]. This involved altering the alerting logic to only consider the horizontal plane, given that vessels can only have an elevation of sea level.

2.2.4 Environmental Effects

To ensure the results of the experiment are applicable to real-world scenarios, the environmental effects will be modelled and included as a disturbance in each of the scenarios. By including the effects of the wind and ocean currents to more closely approximate the natural forces acting on a vessel while at sea, the conclusions drawn from this analysis are applicable to real-world situations. This is accomplished through the Monte Carlo simulation mentioned in subsection 2.2.2, given that environmental conditions are dynamic and change from day-to-day.

Wind conditions

According to Maritime UK's Maritime Autonomous Surface Ships (MASS) UK Industry Conduct Principles and Code of Practice, it is currently recommended that ASVs have set operating limits for wind force according to the Beaufort scale based on the ship's location [22]. These restrictions are outlined in Table 2.2. As a consequence of these limitations placed on the operating capabilities of ASVs, the Monte Carlo analysis performed will factor in these limitations.

Category	Wind Force Limitation [From 0-12]
Ocean	Exceeding 8
Offshore	8
Inshore	6
Sheltered Waters	4

Table 2.2: Wind force limitations for autonomous surface vessels in different operating regions

Referencing wind speed data for St. John's, Newfoundland and Labrador over the 12 month period from June 2020 to June 2021, the highest sustained wind speed was 81 kilometres per hour, measured in December 2020. The highest average wind speed over the course of an entire month was February 2021, with a sustained wind speed average of 31.2 kilometres per hour [23]. This data can be used to build a Gaussian distribution of wind speed for a given time frame, since a normal distribution is applicable to the wind magnitude data.

Ocean currents

When modelling the effects of ocean currents on the ASV during each encounter scenario, the currents can be modelled as a constant velocity which results in a force applied to each vessel. The current data used for the simulation is from the Canadian Department of Fisheries and Oceans for the Gulf of St. Lawrence [24]. Using the most recent data for the year of 2019, the maximum observed surface current was 2.2 knots, while the lowest was 0.8 knots, with the majority of readings coming between these extremes. Once again, this data can be used to build a Gaussian distribution for the expected magnitude of the ocean surface currents that may affect a vessel.

Chapter 3

Modelling and Design of Experiment

Notation used for the extent of the analysis is outlined in the table below.

Symbols	
C	Coefficient
d	Distance
G	Acceleration due to Gravity
h	Height of the Vessel above Waterline
k	Hull Geometry Coefficient
λ	Hull Geometry Coefficient
m	Wave Resistance Coefficient 1
n	Wave Resistance Coefficient 2
N	Moment
ν	Kinematic Viscosity
ψ	Vessel Heading

ρ	Density
$\vec{s}$	Position
SV	Submerged Volume
t	Time
τ	Time-Threshold
u	Surge Speed
v	Sway Speed
$\vec{v}$	Velocity
WA	Wetted Area
WAA	Wetted Area of Appendages
WLL	Water-Line Length
ξ	Wave Resistance Coefficient 3
ζ	Wave Resistance Coefficient 4

Subscripts	
0	Reference
A	Correlation
APP	Appendage
b	Boundary
c	Closest
δ	Rudder
F	Friction
H	Hydrodynamic
i	Intruder
N	Moment

o	Ownship
P	Propeller
R	Water Resistance
TR	Transom Stern
U	Current
W	Wind
WA	Waves
X	Surge Direction
Y	Sway Direction

Table 3.1: Table of variables and subscripts

3.1 Modelling Approach

The example vessel used for the simulations is a container ship with a length of approximately 183 metres, with the physical dimensions obtained from the NRC. The modelling completed on this vessel was using first-principles force modelling and has be outlined in this section.

3.1.1 Surge Motion

The surge motion is described by an initial speed setting for the vessel, along with the net force acting upon the vessel to determine the acceleration calculated at each time-step. The forces considered for the simulation are hydrodynamics, water resistance, wind, surface currents, and the propeller input. The net force equation can be denoted as follows, with F_x for the net surge force, F_{XH} for the hydrodynamic force in the surge direction, F_R for the water resistance force, F_P for the propeller force, F_{WX} for the wind force in the surge direction and F_{UX} for the surface current force in the surge direction.

$$F_x = F_P - F_{XH} - F_R + F_{WX} + F_{UX} \tag{3.1}$$

The propeller force is altered to maintain a desired speed, regardless of the opposing forces. This is discussed in subsection 3.3.1.

Hydrodynamic forces account for the added mass of the vessel due to water. These forces have been described in the background section, and are defined as follows [12]. Let u_0 be the reference surge speed and u be the surge speed of the vessel at a given point in time, with the dot notation being used to denote derivatives.

$$F_{XH} = (u - u_0)\frac{\partial F_{XH}}{\partial u}\bigg|_{u=u_0} + (\dot{u} - \dot{u_0})\frac{\partial F_{XH}}{\partial \dot{u}}\bigg|_{\dot{u}=\dot{u_0}} \tag{3.2}$$

When determining the values of the partial derivative terms in Equation (3.2) the partial derivative with respect to u is an order of magnitude less than the other forces in the surge direction, and therefore assumed to be negligible. The partial derivative with respect to $\dot{u}$ is determined in terms of the vessel dimensions in Clarke, which is used for this model [12].

Next, the water resistance force is determined as a combination of resistance forces on each part of the vessel. The total water resistance force is in Equation (3.3), with R_F as the friction resistance, R_{APP} as the resistance due to appendages, R_{WA} as the resistance due to waves, R_{TR} as the transom stern resistance, and R_A as the correlation resistance. While transom stern resistance is only considered for certain hull types, it is included in this model.

$$F_R = R_F + R_{APP} + R_{WA} + R_{TR} + R_A \tag{3.3}$$

The friction resistance experienced by the ship is defined as follows, where ρ is the density of water, WA is the wetted area of the vessel, WLL is the water-line length of the vessel and ν is the kinematic viscosity of water.

$$R_F = 0.5 * \rho * u^2 * WA * \frac{0.075}{(\log(u * WLL/\nu) - 2)^2} \tag{3.4}$$

Next, the resistance due to appendages can be defined in the following equation, where WAA is the wetted area of appendages and k is a coefficient based on the geometry of the hull obtained from NRC data.

$$R_{APP} = 0.5 * \rho * u^2 * WAA * k * \frac{0.075}{(\log(u * WLL/\nu) - 2)^2} \tag{3.5}$$

The resistance due to waves is defined as follows, where SV is the submerged volume of the vessel, G is the acceleration due to gravity and m, n, ξ, ζ and λ are estimated coefficients based on the dimensions of the particular test vessel.

$$R_{WA} = m * SV * G * \rho * e^{n*(\frac{u}{\sqrt{WLL*G}})^{\xi} + \zeta*\cos(\lambda*(\frac{u}{\sqrt{WLL*G}})^2)} \tag{3.6}$$

The resistance due to the transom stern can be defined in the following equation, where B is the beam length, T is the trim length and r is an estimated coefficient based on the dimensions of the test vessel obtained from NRC data.

$$R_{TR} = 0.5 * \rho * u^2 * B * T * r \tag{3.7}$$

As the final water resistance force, the correlation resistance can be defined as follows, where s is an estimated coefficient based on the dimensions of the vessel.

$$R_A = 0.5 * \rho * u^2 * WAA * s \tag{3.8}$$

Next, the wind force, F_{WX}, is defined as follows, where ρ_{air} is the density of air, h is the height of the vessel above the waterline, and C_{WX} is an estimated coefficient based on the physical dimensions of the vessel.

$$F_{WX} = 0.5 * \rho_a * h * B * C_{WX} * (u_W - u) * |u_W - u| \tag{3.9}$$

Lastly, the current force, F_{CX}, is defined as follows, where C_{CX} is an estimated coefficient based on the physical dimensions of the vessel.

$$F_{CX} = 0.5 * \rho * WLL * (B + T) * C_{CX} * (u_C - u) * |u_c - u| \tag{3.10}$$

3.1.2 Sway Motion

The sway motion describes the movement of the vessel from side to side, or perpendicular to the surge motion. Using a similar approach as the surge motion, the net force on the vessel is calculated at each time-step, which is then used to determine the acceleration of the vessel is this direction. See the following net force equation, where F_y is the sum of the forces in the sway direction, F_{YH} is the hydrodynamic force in the sway direction which includes drag, $F_{Y\delta}$ is the sway force from the rudder, F_{WY} is the force of the wind in the sway direction and F_{CY} is the force of the current in the sway direction.

$$F_y = F_{Y\delta} - F_{YH} + F_{WY} + F_{CY} \tag{3.11}$$

The force, $F_{Y\delta}$, is the sway force that results from the rudder actuating to turn the vessel, and is governed by the below equation which features the partial derivative of the hydrodynamic forces in the sway direction with respect to the rudder position.

$$F_{Y\delta} = \delta \frac{\partial F_{YH}}{\partial \delta}\bigg|_{\delta=0} \tag{3.12}$$

Next, the hydrodynamic force in the sway direction, F_{YH} is described by the following equation, where v is the sway velocity, and ψ is the heading of the vessel.

$$F_{YH} = v\frac{\partial F_{YH}}{\partial v}\bigg|_{v=0} + \dot{v}\frac{\partial F_{YH}}{\partial \dot{v}}\bigg|_{\dot{v}=0} + \dot{\psi}\frac{\partial F_{YH}}{\partial \dot{\psi}}\bigg|_{\dot{\psi}=0} + \ddot{\psi}\frac{\partial F_{YH}}{\partial \ddot{\psi}}\bigg|_{\ddot{\psi}=0} \tag{3.13}$$

The force of the wind in the sway direction, F_{WY}, uses a strip method to analyze the force from the wind on a predefined number of segments along the hull of the vessel. This force is described by the following equation, where C_{WY} is an estimated coefficient based on the physical dimensions of the vessel, a is a variable of summation for the current segment of the ship being analyzed and b is the total number of desired segments.

$$F_{WY} = \sum_{a=0}^{a=b} 0.5 * \rho_a * h * WLL * C_{WY} * (v_{wind} - v - \dot{\psi} * (\frac{-WLL}{2} + \frac{WLL}{b} * a))* \\ |v_{wind} - v - \dot{\psi} * (\frac{-WLL}{2} + \frac{WLL}{b} * a)| \tag{3.14}$$

Lastly, similar to the wind force in the sway direction, the force of the surface current on the vessel in the sway direction is described by the following equation, where C_{CY} is an estimated coefficient based on the physical dimensions of the vessel.

$$F_{CY} = \sum_{a=0}^{a=b} 0.5 * \rho * T * WLL * C_{WY} * (v_{current} - v - \dot{\psi} * (\frac{-WLL}{2} + \frac{WLL}{b} * a))* \\ |v_{current} - v - \dot{\psi} * (\frac{-WLL}{2} + \frac{WLL}{b} * a)| \tag{3.15}$$

3.1.3 Yaw Motion

The yaw moment is characterized by the equation below, showing the net moment acting on the vessel as a consequence of the rudder, hydrodynamics, wind and surface current, where N_δ represents moment from the rudder, N_H represented the moment from the hydrodynamic forces which includes drag, N_W is the moment from the wind, and N_C is the moment from the surface current.

$$N = N_\delta - N_H + N_W + N_C \tag{3.16}$$

The moment caused by the rudder, N_δ, is defined by the following equation, since the rudder is half the length of the vessel from the centre.

$$N_\delta = \delta \frac{WLL}{2} \frac{\partial F_{YH}}{\partial \delta} \bigg|_{\delta=0} \tag{3.17}$$

Next, the moment caused by the hydrodynamic forces acting on the vessel, N_H, is described in the following equation.

$$N_H = v \frac{\partial N_H}{\partial v} \bigg|_{v=0} + \dot{v} \frac{\partial N_H}{\partial \dot{v}} \bigg|_{\dot{v}=0} + \dot{\psi} \frac{\partial N_H}{\partial \dot{\psi}} \bigg|_{\dot{\psi}=0} + \ddot{\psi} \frac{\partial N_H}{\partial \ddot{\psi}} \bigg|_{\ddot{\psi}=0} \tag{3.18}$$

The moment applied to the ship by the wind, N_W, is defined by the following equation. A strip method is used to apply the force at each predefined segment, resulting in the total moment from the wind, where a is the placeholder variable for the segment variable, C_{WN} is an estimated coefficient based on the dimensions of the vessel and b is the desired number of segments for the ship to be divided into. For the test vessel used, it was divided into five equally sized segments to calculate the equivalent moment.

$$\begin{aligned} N_W = \sum_{a=1}^{a=b} 0.5 * \rho_{air} * WLL * h * C_{WY} * (\frac{-WLL}{2} + \frac{a * WLL}{b} - \frac{WLL}{b * 2}) * \\ (v_{wind} - v - \dot{\psi} * a) * |v_{wind} - v - \dot{\psi} * a| \end{aligned} \tag{3.19}$$

For the last contribution to the overall moment on the ship, the moment caused by the surface current, N_C, uses a similar strip method to the wind moment. The following equation represents the sum of the moments on each predefined segment of the vessel.

$$N_C = \sum_{a=1}^{a=b} 0.5 * \rho_{air} * WLL * h * C_{WY} * (\frac{-WLL}{2} + \frac{a * WLL}{b} - \frac{WLL}{b * 2}) * \\ (v_{current} - v - \dot{\psi} * a) * |v_{current} - v - \dot{\psi} * a| \tag{3.20}$$

3.1.4 Wind Modelling

In order to model the wind distribution for the Monte Carlo simulation, some assumptions were made. Given that an encounter could occur with the controlled vessel travelling in a variety of directions, it was assumed that it was equally likely for the wind to be blowing in any direction relative to the heading of the vessel. Additionally, using average wind speed data for the windiest month of the year as outlined in the Background section, a Gaussian distribution for wind speed was allocated, centred about the average and incorporating a variance that allowed the maximum observed sustained wind speed to have a probability of occurrence at approximately 0.1%. See distribution in Figure 3.1 for the wind speed used for the Monte Carlo simulation.

3.1.5 Surface Current Modelling

For the current distribution for the Monte Carlo simulation, it was assumed that the current direction was equally likely to occur in any direction relative to the heading of the vessels. The current data used provides the maximum current magnitude observed on each day. The distribution was constructed using this maximum current, covering the worst case scenario that could potentially be observed. Similar to the approach used for the wind modelling, a Gaussian distribution fit to the current data with the distribution centred at the average maximum current speed of 1.5 knots and a low likelihood of measuring the recorded extremes. See distribution in Figure 3.2 for the

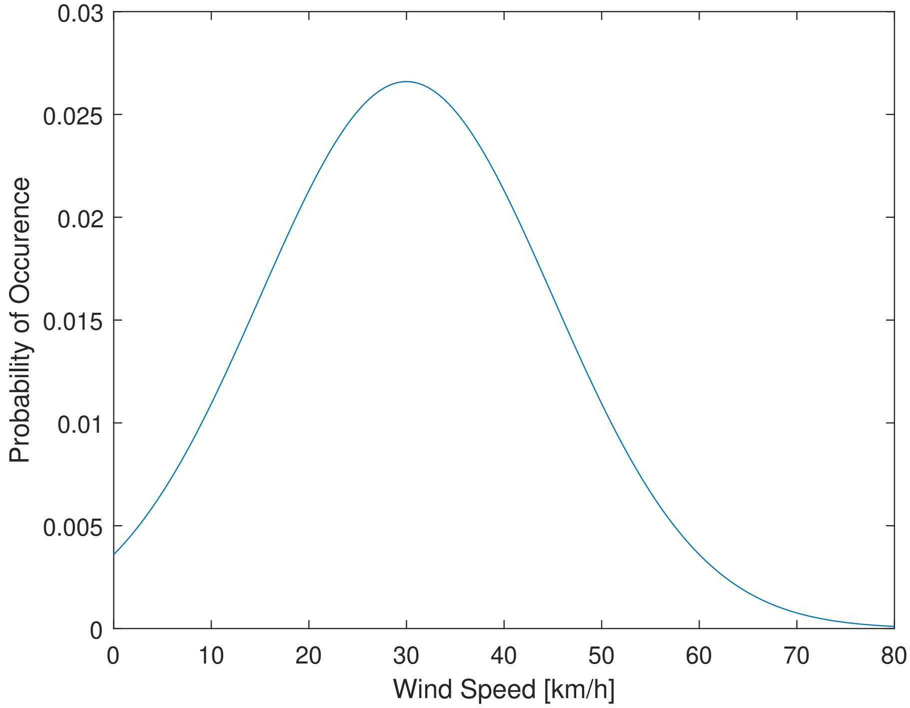

Figure 3.1: Wind distribution used for Monte Carlo simulation

current speed used for the Monte Carlo simulation.

3.2 Simulation

For the simulation aspect, a Monte Carlo approach was selected due to its ability to obtain a specified number of data points for results in a complex simulation, allowing statistical analysis to be performed on these results and obtain a distribution of potential outcomes. The distributions described in Figures 3.1 and 3.2 are converted to meters per second in order to be compatible with the other components of the force model. Additionally, a variety of geometric approach angles for the intruder must be considered in an effort to determine troublesome encounter geometries. Lastly, the methodology for the implementation of the scenarios in Matlab must be considered.

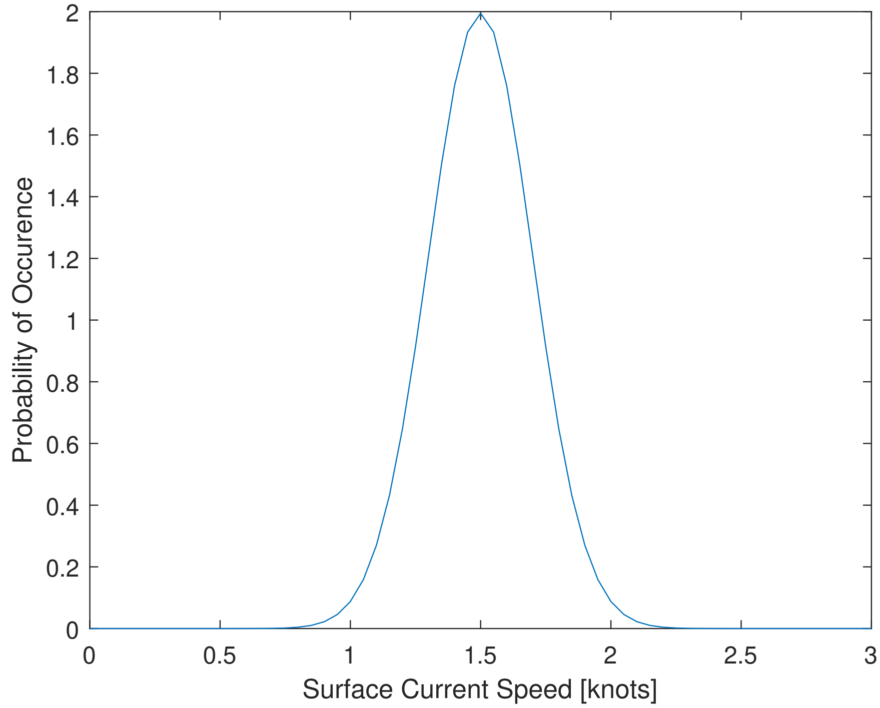

Figure 3.2: Surface current distribution used for Monte Carlo simulation

3.2.1 Monte Carlo Simulation

For the Monte Carlo simulation, the random variables will be modelled to represent the real world scenarios for the angle of approach and offset of the intruding vessel, the wind speed and direction, and the ocean current magnitude and direction. Each trial of the simulation will involve sampling each of the random variables, as per the defined definition and completing the collision avoidance scenario for the given case.

The results are desired to have a 95% confidence interval for the time to react. This high confidence interval is required for the results due to the safety sensitive nature of the analysis being completed.

3.2.2 Geometric Scenarios

For the geometry of the encounters between the controlled vessel and the intruder, there are distinct scenarios outlined in the COLREGs which outline how the controlled vessel must behave. A sample representative of each case will be used in order to ensure that the vessel behaves appropriately. Following this, for the Monte Carlo simulation, the random variables depicting the angle of approach and the offset from the controlled vessel for the intruder will be modelled with an equal likelihood of approach of any angle and any offset, within a range that would cause a near-miss collision for the controlled vessel if no action is to be taken.

3.2.3 Simulation Setup

For the simulation of the encounter scenarios, a time-step of 0.1 seconds was selected, which provides sufficient resolution to observe the desired dynamics of the encounter without making the simulation take prohibitively long to run. In each time-step, the forces on the vessel are considered and applied to the vessel in order to accurately update the velocity and position of the vessel, as well as providing input to the surge and path following controllers. Additionally, the time and distance to the closest point of approach are monitored in order to categorize when an encounter scenario is present.

Each time the controlled vessel fails to maintain a pre-defined separation boundary, the simulation starts over, with the vessel behaviour being modified as per the algorithm outlined in subsection 3.3.3: Collision Avoidance.

3.3 Control Approach

For the given problem of defining a time-based collision avoidance threshold for an encounter between two vessels, there are three distinct parts that need to be controlled while the vessels travel towards their desired destination. These components are the desired speed of the vessel, the desired heading of the vessel and the ability to successfully perform evasive manoeuvres in accordance with the COLREGs in order to maintain a safe degree of separation with both compliant and non-compliant vessels.

3.3.1 Surge Controller

Since there are forces that oppose the propeller force provided by the vessel, the surge speed may vary from the desired set-point. To combat this, a surge controller can be implemented which varies the propeller force in an effort to reach the desired speed of the vessel, regardless of the effects of the wind, currents and water resistance on the speed of the vessel. While on a real vessel the force cannot be explicitly controlled, the speed control on a ship dictates the thrust which can be controlled and varies the force provided by the propeller. Since the net surge force on the vessel cannot be measured to provide a precise, constant opposition propeller force to ensure that the net force on the vessel remains at 0 so that it does not accelerate or decelerate, a Proportional-Integral-Derivative (PID) controller can be implemented which monitors the surge speed and provides feedback to the propeller force.

3.3.2 Path Following

Due to environmental disturbances from the wind and ocean surface currents, the vessel can be deflected from its desired path. The desired path of the vessel can be discretized, and the vessel follow it by using another PID controller that provides input to the rudder based on the perpendicular distance to the nearest point on a tangent to the desired path [25]. This controller is disabled when an encounter scenario is active, since the vessel is responsible for manoeuvring to safety instead of heading toward a destination.

3.3.3 Collision Avoidance

The main focus of this project is the development of the time-based collision avoidance algorithm, determining the last possible second when a turn can be initiated by the controlled vessel in accordance with the COLREGs to avoid a violation of the separation boundary. The alerting logic for the controlled vessel to begin a turn is governed by the following equations from [21]. Let $\vec{s_i}$ be the position of the intruding vessel, $\vec{s_o}$ between the position of the controlled vessel, $\vec{s}$ as the displacement vector between the controlled vessel and the intruder, $\vec{v_i}$ be the velocity of the intruder, $\vec{v_o}$ be the velocity of the controlled vessel and $\vec{v}$ be the relative velocity between the controlled vessel and the intruder.

$$\vec{s} = \vec{s_o} - \vec{s_i} \tag{3.21}$$

$$\vec{v} = \vec{v_o} - \vec{v_i} \tag{3.22}$$

By using these equations, the time to closest point of approach between the two vessels can be determined, and consequently the distance to the closest point of approach can be as well. Let t_c be the time to closest point of approach and d_c be the distance to the closest point of approach.

$$t_c = \begin{cases} \dfrac{-\vec{s} \cdot \vec{v}}{v^2} & \text{if } \vec{v} \neq 0 \\ 0 & \text{otherwise} \end{cases} \tag{3.23}$$

$$d_c = \|\vec{s} + t_c \cdot \vec{v}\| \tag{3.24}$$

The alerting logic uses these quantities in order to determine when the controlled vessel should initiate a turn. In the simulation, once the quantity t_c is equal to the time-threshold quantity, a turn is initiated. During the course of the turn, the required safety boundary is checked to make sure that has not been violated by the intruder. This is checked through the following logical equivalence [21]. Let d_b be the pre-defined safety boundary for the controlled vessel and τ be the time-threshold.

$$A \equiv \|\vec{s}\| \leq d_b \tag{3.25}$$

$$B \equiv d_c \leq d_b \tag{3.26}$$

$$C \equiv 0 \leq t_c \leq \tau \tag{3.27}$$

$$D \equiv A \vee (B \wedge C) \tag{3.28}$$

D in equation (3.8) becomes $TRUE$ if either the distance between the controlled vessel and intruder is less than the safety boundary, or if the boundary will be violated before the vessel begins turning. If D become $TRUE$, the simulation restarts and the value of τ is incremented to increase the time before the closest point of approach that a turn is initiated. Permitted to run enough iterations, the simulation will eventually find the smallest possible time-threshold value to ensure that the vessel has sufficient time to turn and not violate the separation boundary.

3.4 Design of Experiments

The objective for the simulations to be run is to obtain results on the time required to safely maintain a desired separation boundary for a variety of encounter scenarios. In order to do this, each type of encounter - head-on, overtaking and crossing - are analyzed for both a non-compliant and compliant intruder to the COLREGs. Once specific cases have been analyzed for how the controlled vessel performs, a sweep of all possible collision geometries within each type of scenario is performed. The effects of modifying simulation parameters on the performance of the vessel are investigated. Lastly, for identified troublesome encounter geometries with a higher risk of collision, a Monte Carlo simulation is performed to obtain the range of potential performance for randomly sampled environmental conditions.

3.4.1 Non-Compliant Intruder Encounter Scenarios

When analyzing the behaviour of the controlled vessel for an intruder, it is important to consider the possibility that the oncoming vessel or obstacle will not abide by the COLREGs for proper manoeuvring. For these encounters, it is assumed that the intruder is an identical vessel to the controlled vessel and is travelling at the same speed as the controlled vessel. First, each type of encounter scenario will be analyzed, including head-on, overtaking and each type of crossing scenario. For the crossing scenarios, one vessel will have the responsibility of manoeuvring while the other maintains its course, however, if the oncoming vessel is supposed to manoeuvre but does not, the controlled vessel will manoeuvre to avoid a violation of the safety boundary. A summary of the required manoeuvres to be taken by the controlled vessel in each encounter scenario can be found in Table 3.2.

Encounter	Required Manoeuvre by Controlled Vessel
Head-On	Turn to starboard
Crossing intruder approaching from port side	Turn to port
Crossing intruder approaching from starboard side	Turn to starboard
Controlled vessel overtaking	Turn to starboard
Intruding vessel overtaking	Turn to starboard

Table 3.2: Non-compliant intruder encounter scenarios and the required manoeuvres to be taken by the controlled vessel in each instance

Once each independent encounter scenario has been validated for the non-compliant intruder, a sweep of all possible encounter angles being incremented by 0.5 degrees will allow for an exhaustive analysis of the encounter geometry which requires the greatest time to act in order to maintain the desired separation with the intruder.

3.4.2 Compliant Intruder Encounter Scenarios

For the compliant intruder encounter scenarios, this is when the oncoming vessel does abide by the COLREGs and manoeuvres when it is their responsibility to do so. Similar to the non-compliant intruder encounter scenarios, it is assumed that the intruder is an identical vessel to the controlled vessel and is travelling at the same speed as the controlled vessel, unless otherwise specified. Each encounter scenario will be analyzed to ensure that the vessels behave correctly for the head-on, overtaking and crossing scenarios. A summary of the required manoeuvres to be taken by the controlled vessel in each of the encounter scenarios can be found in Table 3.3.

Once the performance of the vessels has been validated for the compliant intruder cases, a sweep of all possible encounter angles will once again be performed by incrementing the encounter angle by 0.5 degrees to perform a complete analysis on all possible encounter angles between the controlled vessel and a compliant intruder.

Encounter	Required Manoeuvre by Controlled Vessel
Head-On	Turn to starboard
Crossing intruder approaching from port side	None
Crossing intruder approaching from starboard side	Turn to starboard
Controlled vessel overtaking	Turn to starboard
Intruding vessel overtaking	None

Table 3.3: Compliant intruder encounter scenarios and the required manoeuvres to be taken by the controlled vessel in each instance

3.4.3 Effects of Modifying Simulation Parameters on Encounter Scenarios

The effects of modifying simulation parameters was considered for analyzing the simulation. The parameters of interest that are modified are the maximum rudder angle of the controlled vessel, size of the desired physical separation boundary, speed of the controlled vessel, direction of both the wind and surface current and magnitude of both the wind and surface current. The parameters to be modified and the expected impact on the minimum time-threshold required by the vessel as the parameters are modified in Table 3.4.

Parameter	Expected Effect on Time-Threshold as Parameter is Increased
Maximum Rudder Angle	Minimal
Size of Separation Boundary	Increase
Speed of Controlled Vessel	Decrease
Wind Direction/Magnitude	Varies
Surface Current Direction/Magnitude	Varies

Table 3.4: Simulation parameters to be modified for all encounter geometries and the expected effects on the time-threshold as each parameter is modified

3.4.4 Monte Carlo Simulation for Environmental Conditions

In order to properly gauge the impacts of weather conditions on the ability of the controlled vessel to manoeuvre as required to maintain the desired separation boundary with an intruder, the wind and surface current direction and magnitude have been modelled as random variables, as described in the Theory chapter. In order to obtain an adequate measure of the range of potential outcomes, a Monte Carlo simulation is performed by sampling the environmental condition random variables for a large number of trials and obtaining confidence intervals for the time required to manoeuvre for identified high-risk encounter geometries.

Chapter 4

Simulation Results and Analysis

4.1 Non-Compliant Intruder Encounter Scenarios

The non-compliant intruder example encounter scenarios were run for each scenario at 0/90/180/270 degrees, which include head-on, overtaking, crossing where the controlled vessel is expected to manoeuvre and crossing whereby it is the intruder's responsibility to manoeuvre. A sweep analysis was performed to analyze the behaviour of the vessel for not directly aligned encounters for each type of encounter. For all trials, unless otherwise specified, the vessels are travelling at the same speed with a desired separation boundary for the controlled vessel of twice the length of the vessel from the centre and no surface current or wind. The blue path represents the path of the controlled vessel, while the red path represents the path of the intruder, while the green circle indicates the desired separation boundary and the green rectangle the approximate size of the controlled vessel. In each of these simulations, the encounters occur with no wind and calm water.

4.1.1 Non-Compliant Intruder Head-On Encounter

For the example non-compliant head-on encounter case, the vessels were pointed directly towards each other at the same speed, with only the controlled vessel manoeuvring to safety when both vessels should be acting. See Figures 4.1, 4.2 and 4.3 for the path of the vessels for the encounter scenario for the trial whereby the controlled vessel maintains the desired separation boundary. Since this is the first example encounter observed in this work, multiple plots are used to illustrate the path of the vessel throughout the encounter whereby the vessel is turning at the time-threshold. The time-threshold required to achieve this is 179 seconds.

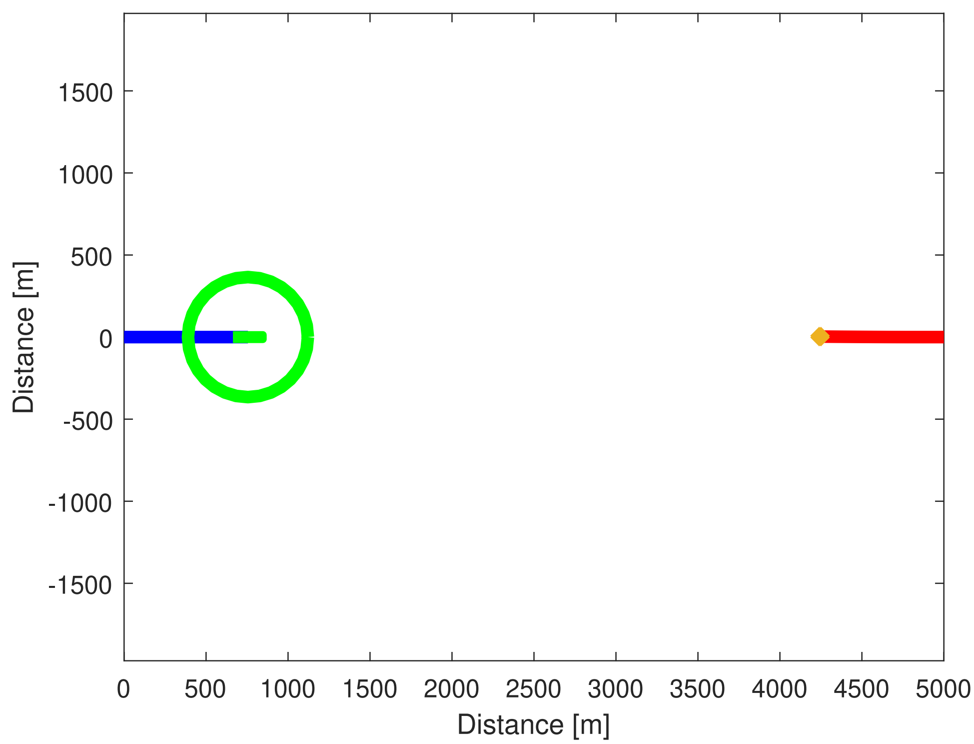

Figure 4.1: Non-compliant intruder typical head-on encounter scenario prior to engaging in a manoeuvre

In order to perform a robust analysis of the time-threshold required for any head-on

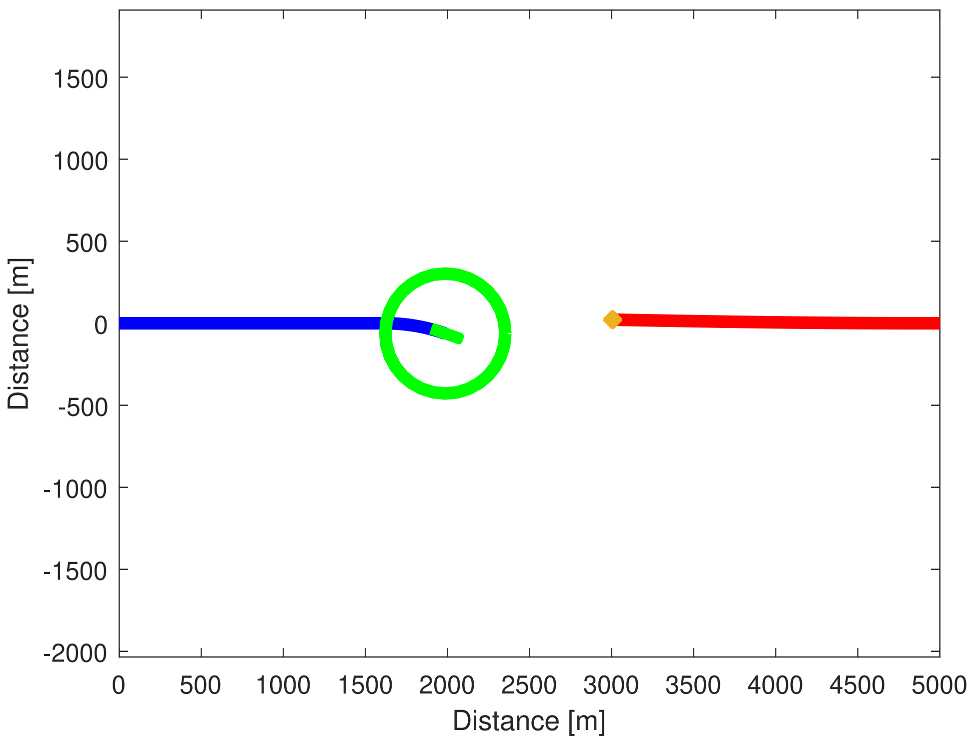

Figure 4.2: Non-compliant intruder typical head-on encounter scenario when the turn is initiated

encounter, all head-on encounter angles must be accounted for in order to determine how the angle of encounter affects the time-threshold. The COLREGs define a head-on encounter scenario as one that occurs when an oncoming vessel approaches from 22.5 to -22.5 degrees of the controlled vessel's heading. For this analysis, every 0.5 degree step between the aforementioned headings was run in order to obtain the required time-thresholds, presented in Figure 4.4. The required time to manoeuvre varies from 178 seconds to 183 seconds, as can be seen in the figure. Each point on the figure indicates where the oncoming intruder is travelling from, relative to the controlled vessel with a heading of 0 degrees.

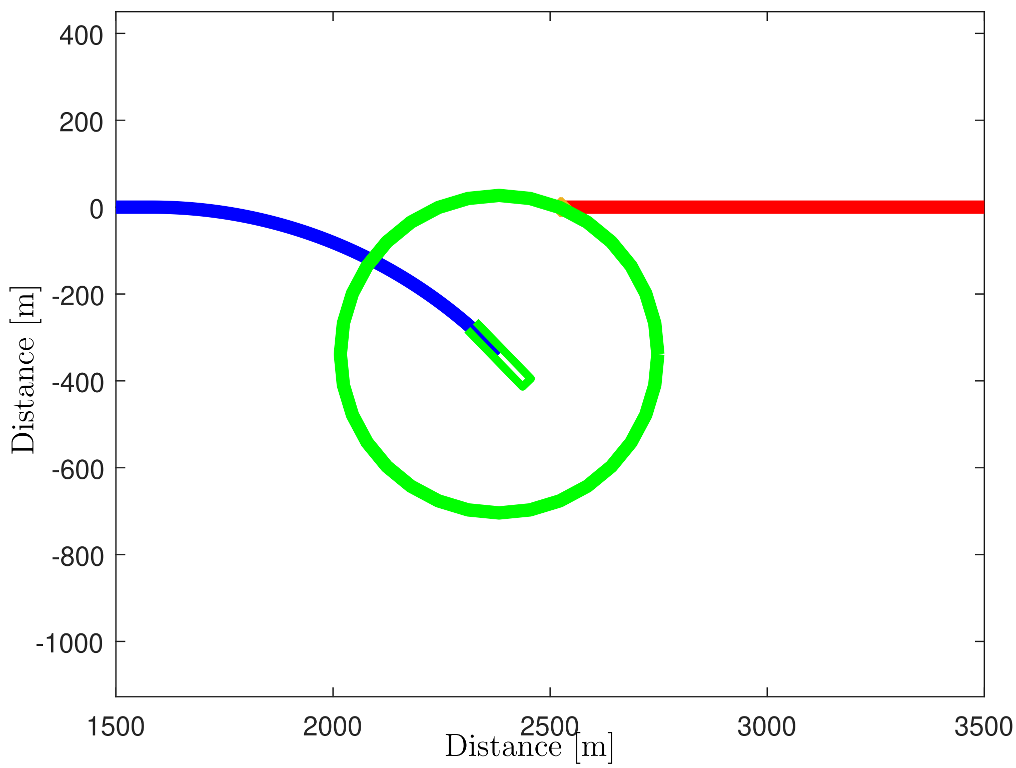

Figure 4.3: Non-compliant intruder typical head-on encounter scenario

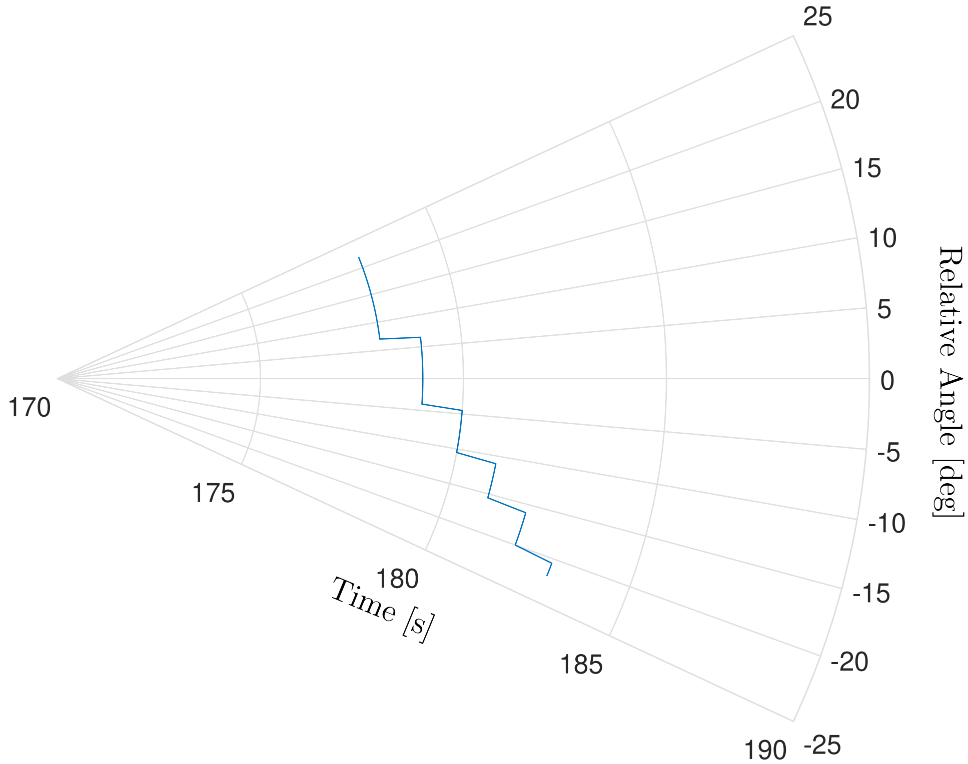

Figure 4.4: Non-compliant intruder head-on encounter scenario for all encounter angles

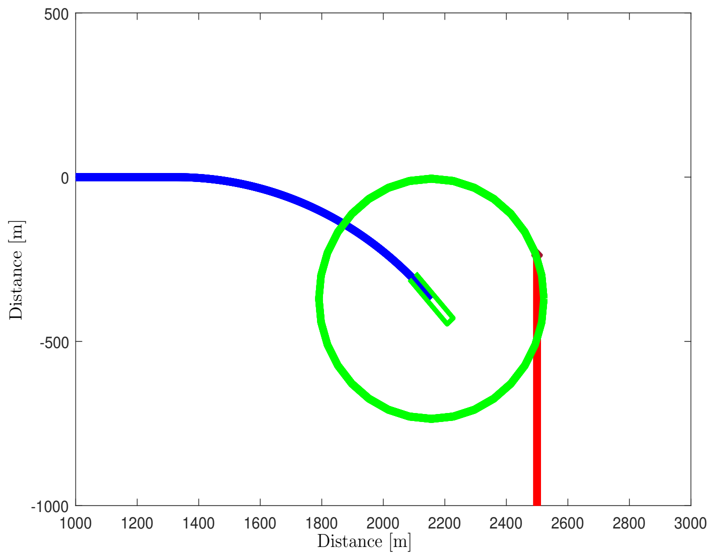

Figure 4.5: Non-compliant intruder crossing encounter scenario for controlled vessel manoeuvring responsibility example

4.1.2 Non-Compliant Intruder Crossing Encounters

The first crossing encounter to be analyzed for the non-compliant crossing cases is the case whereby the controlled vessel is responsible for manoeuvring. This will be the same as the compliant crossing case for when the controlled vessel is responsible for manoeuvring, since the other vessel should keep their course and not manoeuvre. The heading angle between the controlled vessel and the oncoming intruder is exactly 90 degrees for this example. See Figure 4.5 for the path of the vessels near the encounter point for the trial when the controlled vessel maintains the desired separation boundary. This is attained when the controlled vessel begins turning 228 seconds prior to what would be the collision point.

Similar to the exhaustive analysis performed for the head-on encounter scenarios, a similar analysis will be performed for crossing encounters where the controlled vessel is responsible for manoeuvring, with the intruder approaching from 202.5 to 337.5

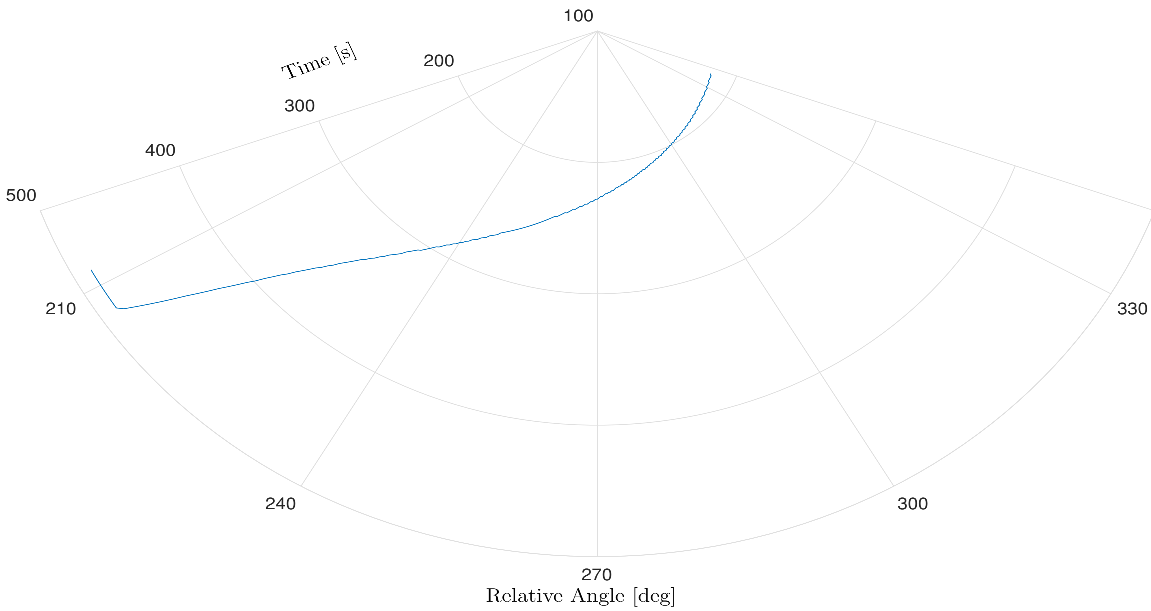

Figure 4.6: Non-compliant intruder crossing encounter scenario for controlled vessel manoeuvring responsibility for all encounter angles

degrees. See Figure 4.6 for the results of this analysis. Given that this is the scenario whereby the controlled vessel is responsible for manoeuvring, the results will be the same for the compliant intruder crossing case. When the intruder approaches from 202.5 to 208 degrees, the controlled vessel is unable to manoeuvre to preserve the safety boundary, since the intruding vessel is travelling at the same speed, and this is nearly an overtaking scenario. For this encounter, no manoeuvring is required since the intruder will not overtake the controlled vessel. The time required to manoeuvre varies from 183 to 483 seconds, with the lesser time corresponding to crossing scenarios which are near to head-on encounter angles, while the longer times corresponding to near overtaking scenarios.

The other crossing encounter scenario, when the intruder is responsible for manoeuvring is also analyzed. In this case, the controlled vessel would need to be aware that the oncoming vessel is not complying with the COLREGs when it is their responsibility to manoeuvre, and begin manoeuvring to preserve the desired safety boundary.

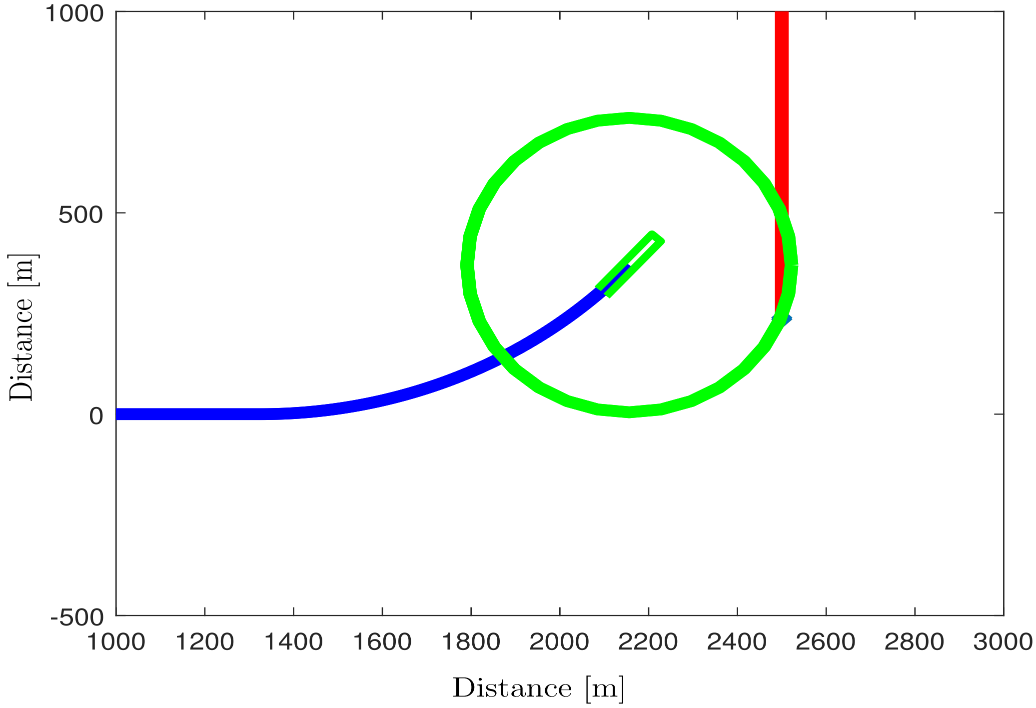

Figure 4.7: Non-compliant intruder crossing encounter scenario for intruding vessel manoeuvring responsibility example

The heading angle between the controlled vessel and the intruder is exactly 270 degrees. See Figure 4.7 for the path of the vessels for this encounter scenario. Similar to the previous case, the time-threshold required to maintain the separation boundary is 228 seconds.

Once again, the sweep analysis was performed for all encounter angles with a non-compliant intruder in a crossing scenario whereby the intruding vessel is responsible for manoeuvring. In this case, the intruder approaches from between 22.5 and 157.5 degrees, with every 0.5 degree step being checked. See Figure 4.8 for the results of this analysis. From 152 to 157.5 degrees, a similar issue arises to the other crossing case, in that it creates a near overtaking scenario. Since the vessels are travelling at the same speed, the controlled vessel cannot manoeuvre safely. Like the previous case,

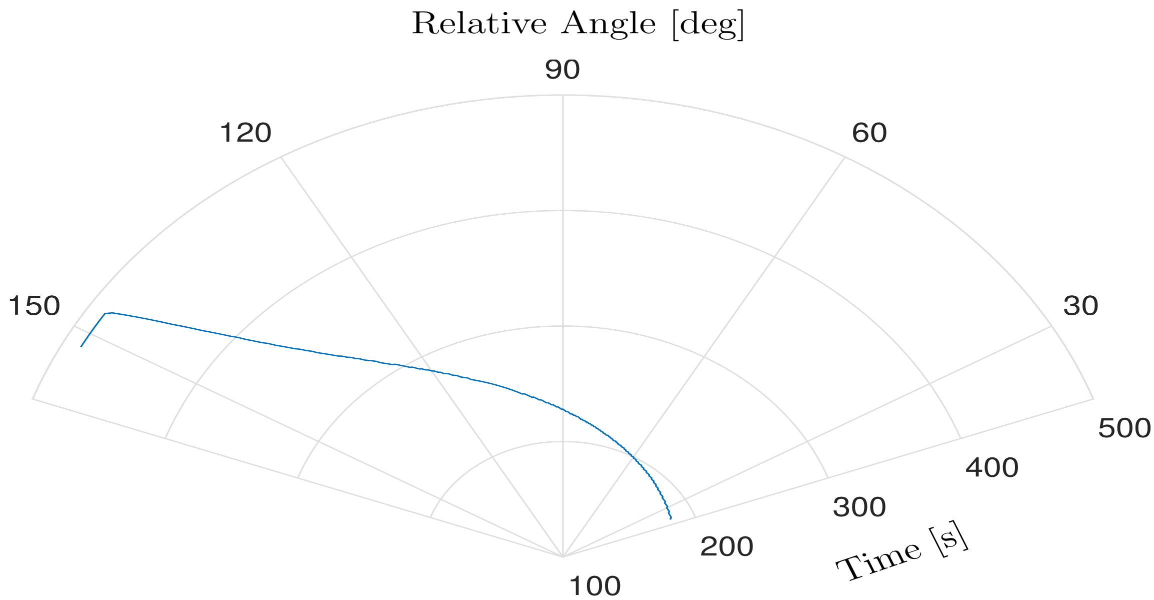

Figure 4.8: Non-compliant intruder crossing encounter scenario for intruding vessel manoeuvring responsibility for all encounter angles

the time required to manoeuvre ranges from 183 to 483 seconds, with the lesser times corresponding to encounter angles nearer to a head-on encounter geometry, with the greater times corresponding to the encounter angles nearer to overtaking scenarios.

4.1.3 Non-Compliant Intruder Overtaking Encounter

Lastly, for the non-compliant intruder overtaking encounters, this is similar to the crossing encounter, where the vessel being overtaken is expected to just keep the course. For these example simulations, the vessel being overtaken is travelling at 80% of the speed of the overtaking vessel. The first encounter to be analyzed is when the controlled vessel overtakes the intruder. The behaviour of the vessels in this encounter would be the same as for the compliant intruder case. Each of the vessels will have an identical heading for this example. See Figure 4.9 for the path of the vessels in this encounter. The controlled vessel must begin turning 487 seconds before the closest

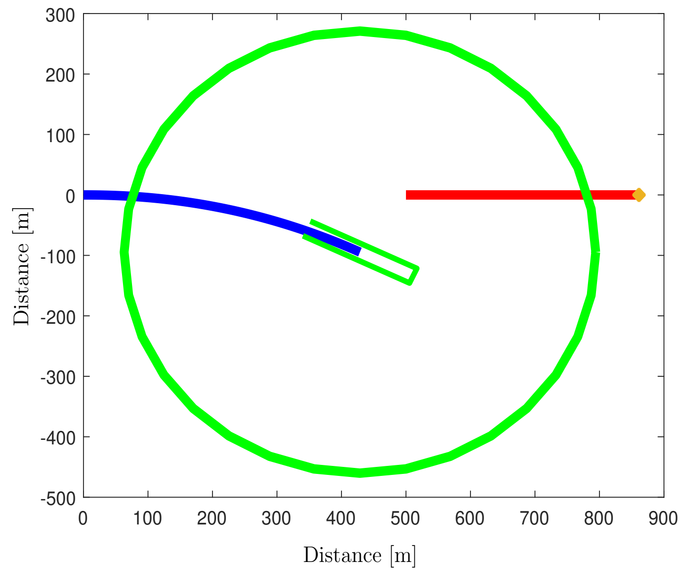

Figure 4.9: Non-compliant intruder overtaking encounter scenario for controlled vessel manoeuvring responsibility example

point of approach in order to maintain the desired separation boundary.

The sweep analysis is performed for when the controlled vessel is overtaking the intruder, when the headings are aligned in roughly the same direction, with the intruder's heading being between -22.5 and 22.5 degrees. See Figure 4.10 for the results of the analysis. The time required for the controlled vessel to manoeuvre ranges from 230 to 487 seconds, with the lesser time corresponding to overtaking scenarios where the intruder vessel is coming from the port side of the vessel, and the longest times are from the directly aligned heading to coming from 10 degrees to the starboard side of the controlled vessel.

For the alternate overtaking case, whereby the controlled vessel is being overtaken and the intruder is non-compliant, meaning that they are supposed to manoeuvre around the controlled vessel, but does not, the controlled vessel will have to manoeuvre to maintain the safety boundary. In this case, the controlled vessel is travelling at

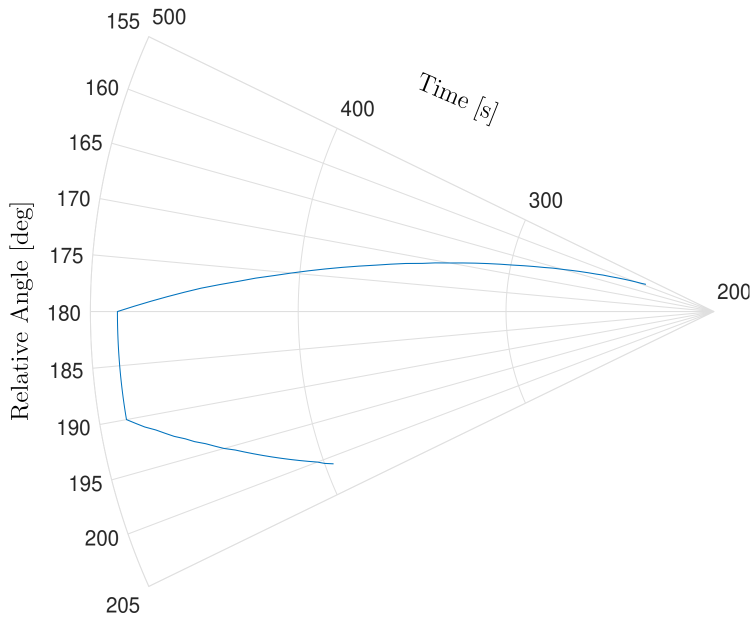

Figure 4.10: Non-compliant intruder overtaking encounter scenario for controlled vessel manoeuvring responsibility for all encounter angles

80% of the speed of the intruder. See Figure 4.11 for the path of the vessels for this encounter. The controlled vessel must begin the manoeuvre 527 seconds prior to the closest point of approach in order to maintain the desired boundary.

For the analysis of all encounter angles for when the non-compliant intruder is overtaking the controlled vessel, when the intruding vessel is coming from the starboard side of the controlled vessel, the controlled vessel must turn to port side in order to maintain separation with the intruder. The starboard turn can remain for the cases when the intruder comes from the port side. This results in the symmetrical plot seen in Figure 4.12. The time required to manoeuvre safely ranges from 527 seconds when the headings are directly aligned to 241 seconds when they are least aligned.

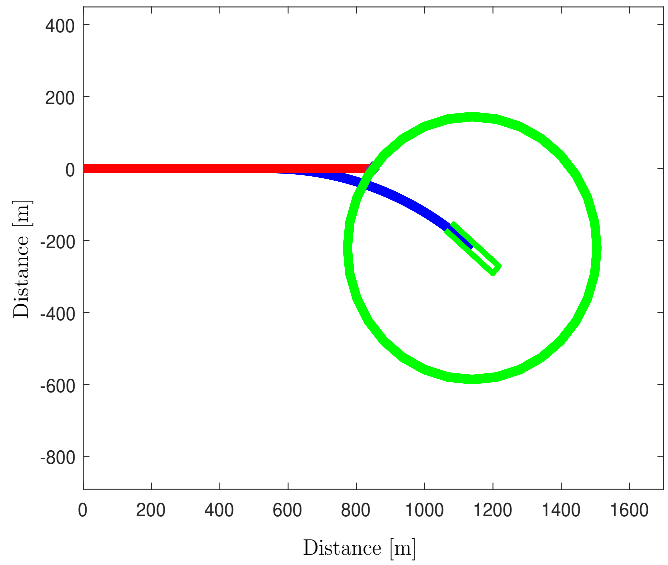

Figure 4.11: Non-compliant intruder overtaking encounter scenario for intruding vessel manoeuvring responsibility example

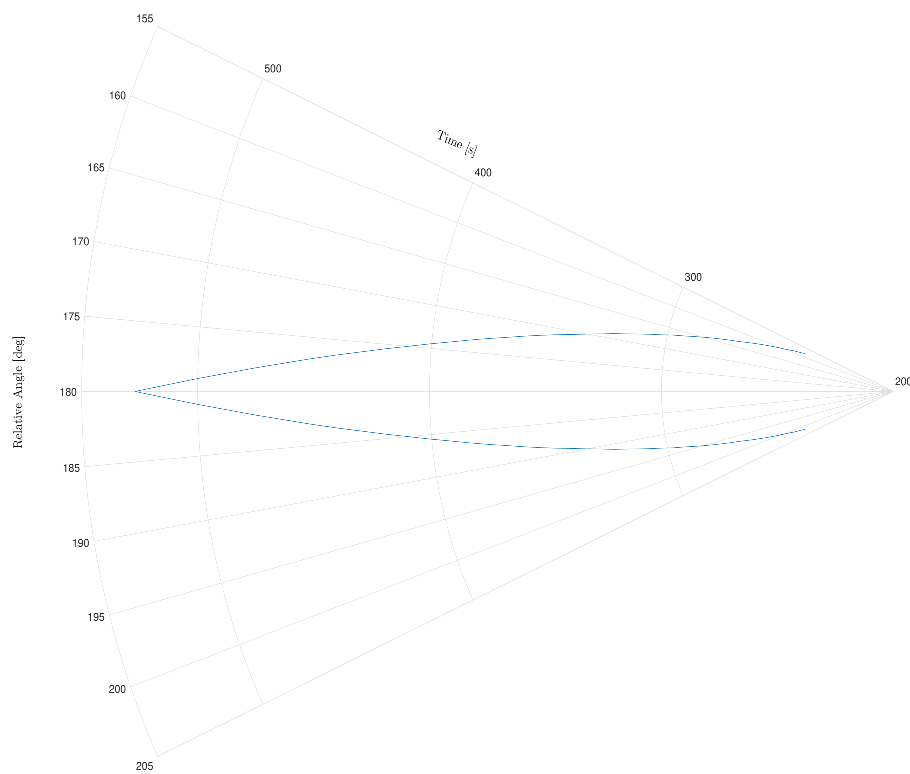

Figure 4.12: Non-compliant intruder overtaking encounter scenario for intruding vessel manoeuvring responsibility for all encounter angles

4.2 Compliant Intruder Encounter Scenarios

Similar to the non-compliant encounter scenarios, an example encounter will be run for each type of example geometry when the controlled vessel is expected to manoeuvre, including head-on, overtaking and crossing. In addition, a sweep analysis will be performed for each encounter geometry to understand how the time-threshold required changes. For all trials, unless otherwise specified, both vessels are travelling at the same speed, in the absence of any surface current or wind. Both vessels are identical. The desired separation boundary for the controlled vessel and the oncoming vessel will be twice the length of the vessel. Once again, the blue path represents the path of the controlled vessel, the red path for the intruding vessel, the green circle for the size of the separation boundary for the controlled vessel and the green rectangle for the approximate outline of the controlled vessel. In each of these simulations, the encounters occur with no wind and calm water.

4.2.1 Compliant Intruder Head-On Encounter

For the compliant intruder head-on encounter, both vessels are responsible for turning. In the example encounter seen in Figure 4.13, both vessels have a heading directly towards one another. In this case, the controlled vessel must have a time-threshold of 130 seconds, a noticeable improvement from the 179 seconds required for the non-compliant intruder head-on encounter.

Again, the COLREGs define a head-on encounter as one that occurs when two vessels are headed towards one another within the range of -22.5 to 22.5 degrees. In this encounter scenario, both vessels are expected to manoeuvre to starboard side of the vessel in order to maintain distance with one another. See in Figure 4.14 the

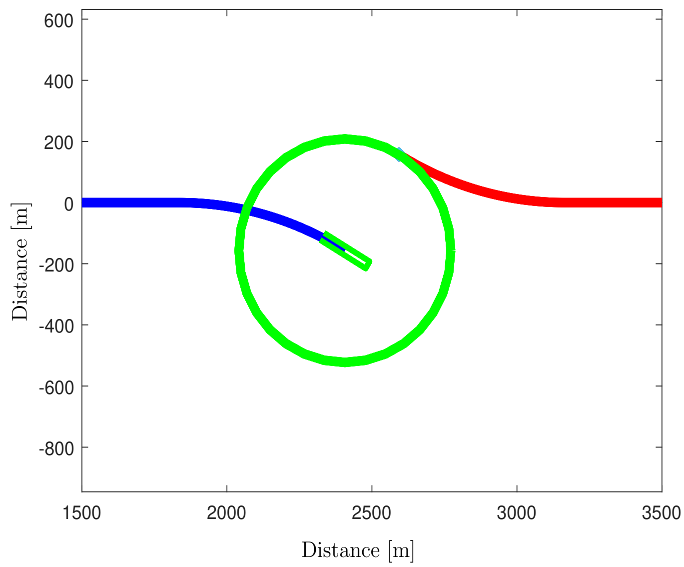

Figure 4.13: Compliant intruder head-on encounter scenario example

results of determining the time-threshold required for all encounter angles in this range, at 0.5 degree steps. The time required to safely manoeuvre varies from 130 to 132 seconds.

4.2.2 Compliant Intruder Crossing Encounter

The compliant intruder crossing encounter of interest is when the controlled vessel is responsible for manoeuvring around the intruder. In this case, the encounter will be the same as the non-compliant intruder case, since the intruder is not supposed to manoeuvre. See Figure 4.15 for the example encounter scenario, the same paths taken by the vessels as in Figure 4.5.

When analyzing the time-threshold required for all crossing encounters where the controlled vessel is responsible for manoeuvring, this will be the same as the non-compliant cases, since the COLREGs specify that the intruder should keep course in this situation. Similarly, the time required to manoeuvre varies from 183 to 483

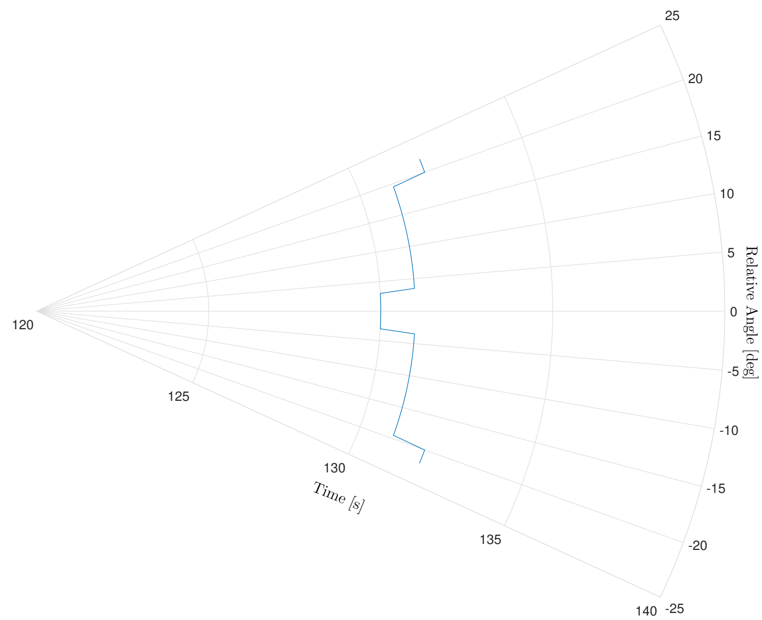

Figure 4.14: Compliant intruder head-on encounter scenario for all encounter angles

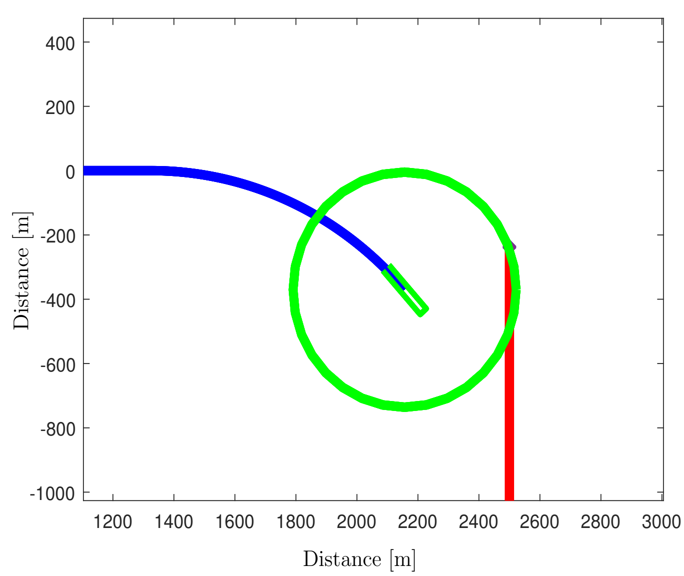

Figure 4.15: Compliant intruder crossing encounter scenario with controlled vessel responsible to manoeuvre example

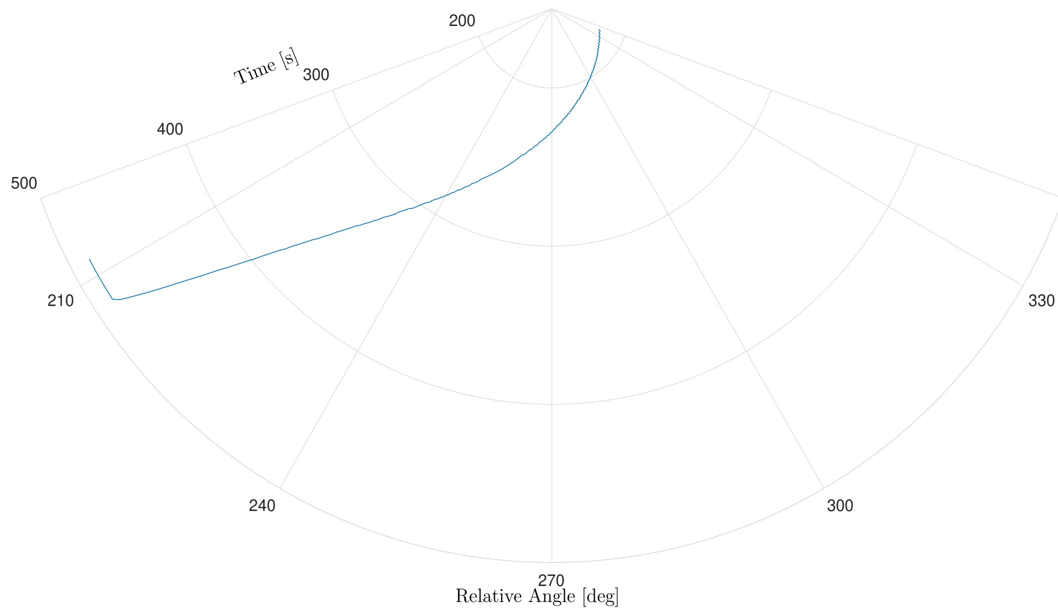

Figure 4.16: Compliant intruder crossing encounter scenario with controlled vessel responsible to manoeuvre for all encounter angles

seconds, with the lesser time corresponding to crossing scenarios which are near to head-on encounter angles, while the longer times corresponding to near overtaking scenarios.

For the crossing case whereby the intruder is responsible for manoeuvring, the controlled vessel should keep its course. Therefore, there is no time-threshold for this scenario. See Figure 4.17 for the paths of the vessels for this encounter. There is also no analysis performed for all encounter angles for this scenario, since the controlled vessel does not manoeuvre.

4.2.3 Compliant Intruder Overtaking Encounter

The last encounter scenario for the compliant intruder is the overtaking scenario. In this case, whether the intruder is overtaking or the controlled vessel is overtaking, the paths will look identical, since the vessels are assumed to be identical. Similar to the

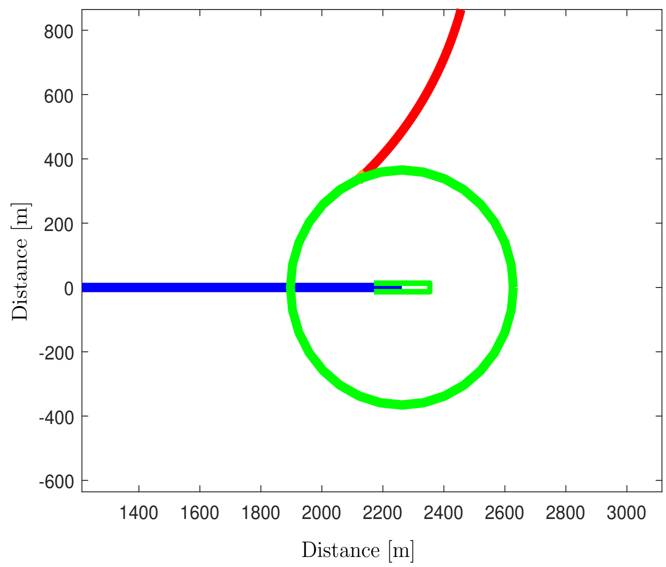

Figure 4.17: Compliant intruder crossing encounter scenario with intruding vessel responsible to manoeuvre example

non-compliant intruder overtaking case, the vessel being overtaken is travelling at 0.8 times the speed of the overtaking vessel. To be compliant with the COLREGs, the vessel being overtaken keeps its course, while the overtaking vessel is required to turn. See Figure 4.18 for the example encounter scenario.

Similar to the crossing scenario outlined in the previous subsection, the overtaking scenario for the controlled vessel manoeuvring responsibility is the same for both the non-compliant and compliant cases, since the intruding vessel is supposed to maintain its course. For the overtaking case whereby the intruder is responsible to manoeuvre, there is no time-threshold for the compliant intruder case, since the controlled vessel is supposed to maintain its course. See Figure 4.19 for the results of all encounter angles for the compliant intruder where the controlled vessel is responsible for manoeuvring.

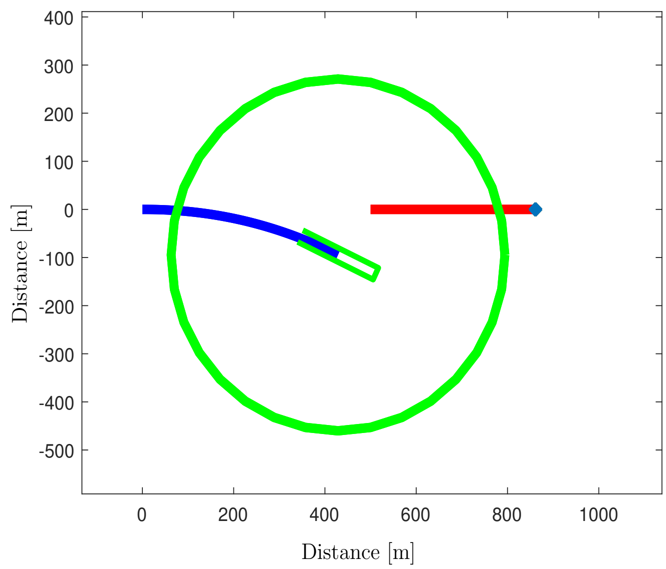

Figure 4.18: Compliant intruder overtaking encounter scenario example

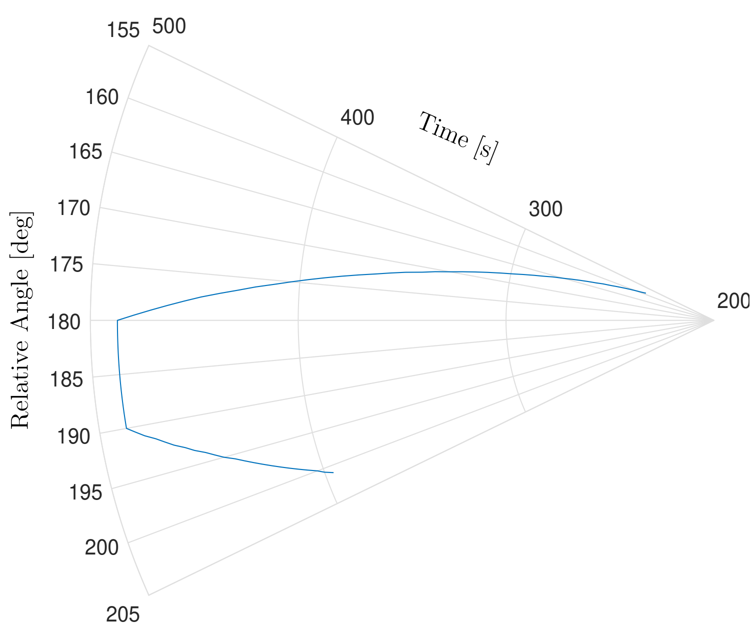

Figure 4.19: Compliant intruder overtaking encounter scenario for controlled vessel manoeuvring responsibility for all encounter angles

4.3 Effects of Modifying Simulation Parameters on Encounter Scenarios

When analyzing the performance of the vessel in the simulation, it is important to have context surrounding how assumed parameters affect the results provided. These assumed parameters including the maximum rudder deflection angle, the speed of the controlled vessel and the size of the desired self-separation boundary. The effects of these quantities will be analyzed for both the non-compliant and compliant encounter scenarios, for each of the example collision geometries in the previous section whereby the controlled vessel is responsible for manoeuvring. Initially, the controlled vessel has a maximum rudder deflection angle of 5 degrees, a speed of 10 knots and a desired safety boundary of twice the length of the ship from the centre point.

4.3.1 Effects of Modifying Parameters on Non-Compliant Intruder Encounter Scenarios

To analyze the effects of changing the parameters on the time-threshold required for the encounter scenario, each of the parameters outlined are set to 50%, 75%, 100%, 125% and 150% of the nominal value in order to see the trends for each encounter geometry. See Tables 4.1, 4.2 and 4.3 for the effects of modifying each of the parameters on the time-threshold for each of the collision geometry examples. In the columns entitled “Time % Change”, a negative number refers to the time-threshold required to safely manoeuvre decreasing, while a positive number refers to the time-threshold required increasing. Note that for the overtaking encounter scenario, the controlled vessel speed could not be reduced to 75% or 50% of the original, since it would then be going slower than the vessel that it is attempting to overtake.

% of Original Parameter Value	Time % Change Due to Max Rudder Deflection Angle	Time % Change Due to Controlled Vessel Speed	Time % Change Due to Safety Boundary Size
50	2.23	41.90	-29.61
75	1.12	15.64	-13.41
100	0	0	0
125	-0.56	-10.61	12.29
150	-1.68	-17.32	22.91

Table 4.1: Simulation parameters modified for the non-compliant head-on encounter scenario and effects on the time-threshold required

% of Original Parameter Value	Time % Change Due to Max Rudder Deflection Angle	Time % Change Due to Controlled Vessel Speed	Time % Change Due to Safety Boundary Size
50	1.32	57.46	-30.70
75	0.44	23.25	-14.47
100	0	0	0
125	-0.88	-15.79	12.28
150	-1.75	-26.32	24.12

Table 4.2: Simulation parameters modified for the non-compliant crossing encounter scenario and effects on the time-threshold required

% of Original Parameter Value	Time % Change Due to Max Rudder Deflection Angle	Time % Change Due to Controlled Vessel Speed	Time % Change Due to Safety Boundary Size
50	0		-51.95
75	0		-29.36
100	0	0	0
125	-0.62	-48.87	5.54
150	-0.82	-59.96	23.41

Table 4.3: Simulation parameters modified for the non-compliant overtaking encounter scenario and effects on the time-threshold required

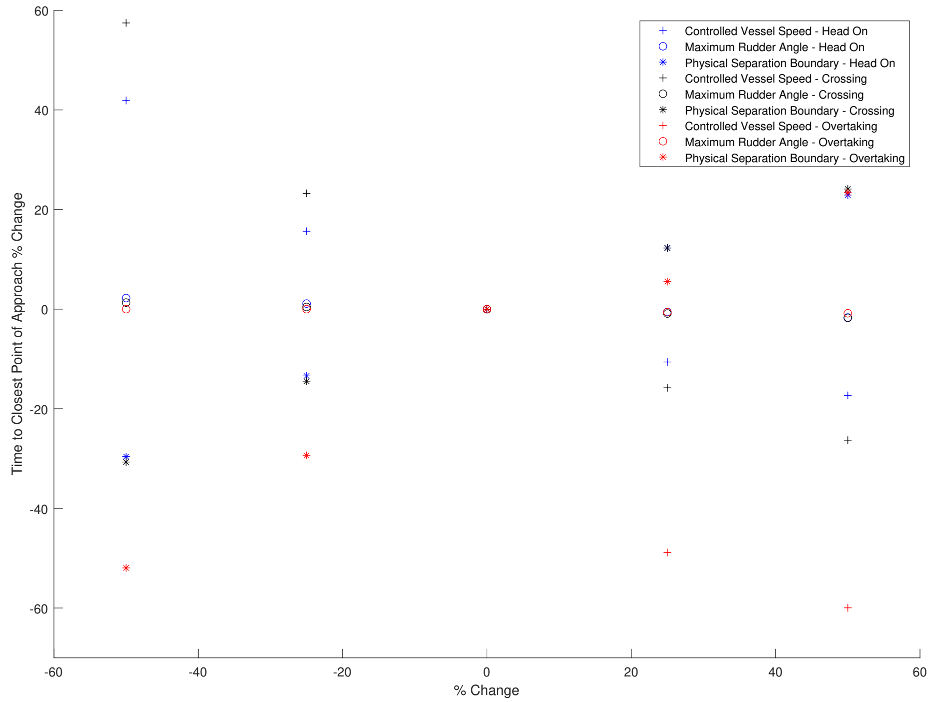

Figure 4.20: Effects of modifying parameters on time-threshold for each example encounter geometry for a non-compliant intruder

See Figure 4.20 for the plot of the data in Tables 4.1, 4.2 and 4.3. From this data, the maximum rudder deflection angle for the controlled vessel has minimal effect on the time-threshold. Additionally, the faster the controlled vessel is travelling towards the intruder, the less time is required to safely manoeuvre, and the inverse is also true for when the vessel travels slower. Lastly, the smaller the desired safety boundary, the smaller the required time-threshold is. Once again, the inverse is true for when the size of the safety boundary is increased.

4.3.2 Effects of Modifying Parameters on Compliant Intruder Encounter Scenarios

The same study will be performed for the compliant intruder head-on, crossing and overtaking encounter examples where the controlled vessel is responsible for manoeuvring. This results in the same results for both the crossing and overtaking scenarios, since the intruder is not responsible for manoeuvring in either case. See Tables 4.4, 4.5 and 4.6 for the results of changing the parameters on the required time-threshold.

% of Original Parameter Value	Time % Change Due to Max Rudder Deflection Angle	Time % Change Due to Controlled Vessel Speed	Time % Change Due to Safety Boundary Size
50	1.45	19.57	-30.43
75	0.72	8.70	-13.77
100	0	0	0
125	-0.72	-7.25	13.04
150	-0.72	-12.32	24.64

Table 4.4: Simulation parameters modified for the compliant head-on encounter scenario and effects on the time-threshold required

% of Original Parameter Value	Time % Change Due to Max Rudder Deflection Angle	Time % Change Due to Controlled Vessel Speed	Time % Change Due to Safety Boundary Size
50	1.32	57.46	-30.70
75	0.44	23.25	-14.47
100	0	0	0
125	-0.88	-15.79	12.28
150	-1.75	-26.32	24.12

Table 4.5: Simulation parameters modified for the compliant crossing encounter scenario and effects on the time-threshold required

See the data in Tables 4.4, 4.5 and 4.6 plotted in Figure 4.20. The trends remain the same from the non-compliant intruder cases.

% of Original Parameter Value	Time % Change Due to Max Rudder Deflection Angle	Time % Change Due to Controlled Vessel Speed	Time % Change Due to Safety Boundary Size
50	0		-51.95
75	0		-29.36
100	0	0	0
125	-0.62	-48.87	5.54
150	-0.82	-59.96	23.41

Table 4.6: Simulation parameters modified for the compliant overtaking encounter scenario and effects on the time-threshold required

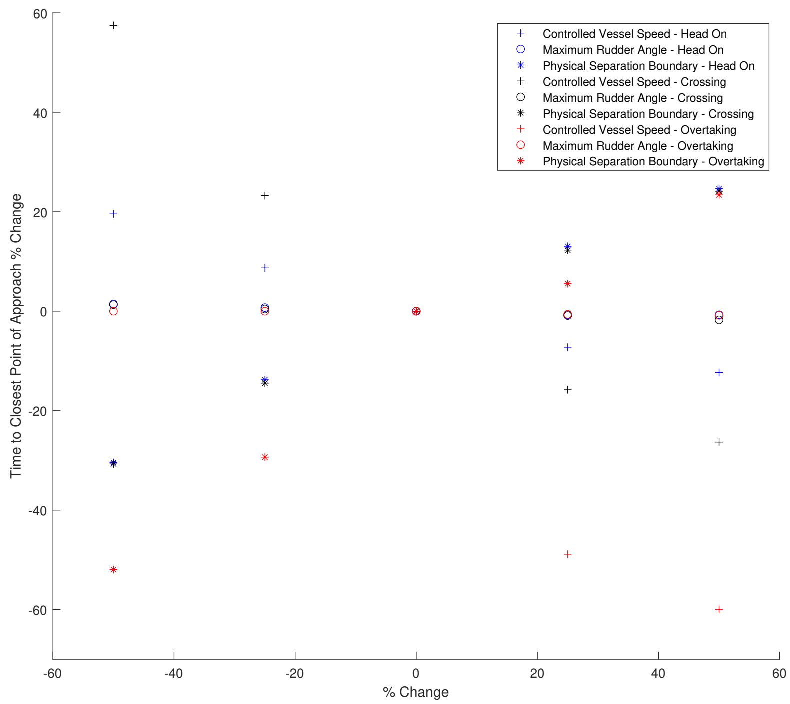

Figure 4.21: Effects of modifying parameters on time-threshold for each example encounter geometry for a compliant intruder

4.4 Monte Carlo Simulation for Environmental Conditions

In order to capture the effects of the disturbance of environmental conditions on the encounter scenarios outlined in the previous sections, the effects of environmental conditions such as the wind and surface currents must be considered. In order to complete this analysis, the wind and surface current distributions modelled in the Theory section in Figures 3.1 and 3.2. For each distinct scenario that has different results from the previous section, a Monte Carlo simulation was run with N=1000 to demonstrate the possible range of outcomes.

4.4.1 Non-Compliant Head-On Intruder Case

For the non-compliant intruder head-on encounter case, a Monte Carlo simulation was performed in order to obtain an idea of the possible range of outcomes when the vessels in the simulation are subjected to environmental conditions. See the results histogram in Figure 4.22 for a Monte Carlo simulation with N=1000. As can be seen in the histogram, the smallest time-threshold required for any of the trials is 171 seconds, while the largest is 487 seconds. The time-threshold required to cover 95% of all runs in the Monte Carlo simulation is 322 seconds. This is compared to 179 seconds for the time-threshold in the case without environmental conditions. See Figure 4.23 for the best and worst case scenarios from the Monte Carlo simulation performed.

4.4.2 Compliant Head-On Intruder Case

For the compliant intruder head-on on case, another Monte Carlo simulation was performed with N=1000. See histogram of relative probabilities for the time-threshold required for safe navigation with environmental conditions for a Monte Carlo simulation with N=1000 in Figure 4.24. From the histogram, the smallest required time-threshold is 125 seconds, while the largest required time-threshold is 274 seconds, 95% of the encounters requiring a time-threshold of less than 228 seconds. This

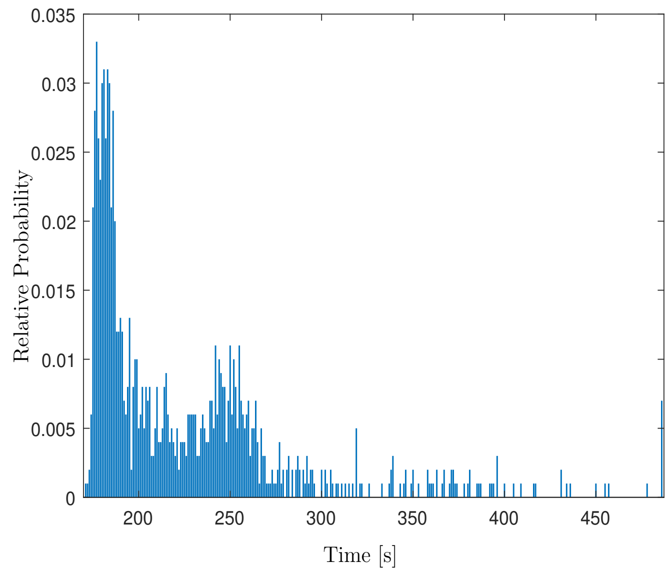

Figure 4.22: Non-compliant intruder head-on encounter Monte Carlo simulation for environmental conditions with N=1000

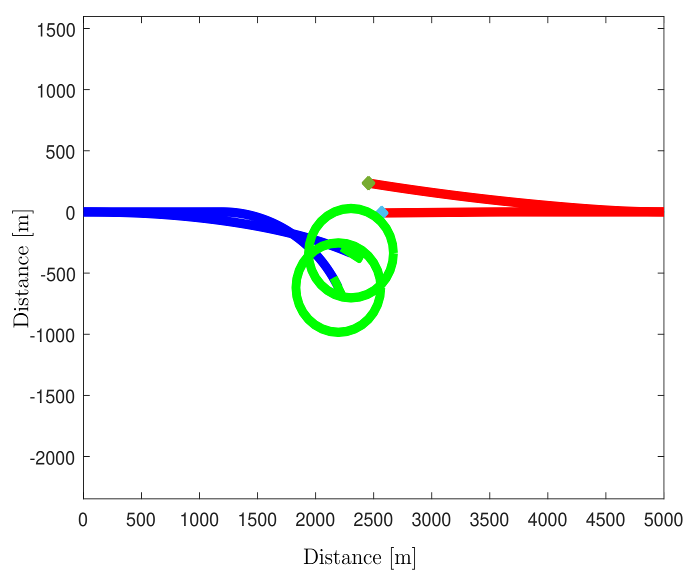

Figure 4.23: Non-compliant intruder head-on encounter scenarios for best and worst case scenarios in Monte Carlo simulation

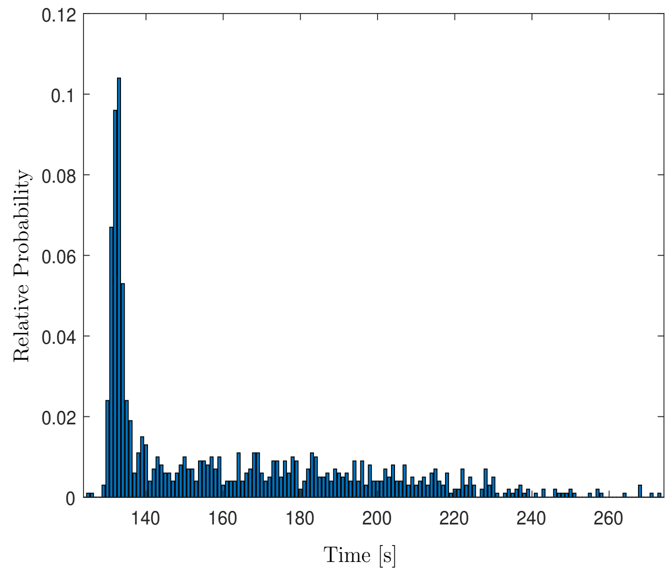

Figure 4.24: Compliant intruder head-on encounter Monte Carlo simulation for environmental conditions with N=1000

compares with the case without environmental conditions present, which results in a time-threshold of 130 seconds. See Figure 4.25 for the best and worst case scenarios from the Monte Carlo simulation.

4.4.3 Crossing Intruder Case

For the crossing intruder case, another Monte Carlo simulation was performed with N=1000. See histogram of relative probabilities for the time-threshold required for safe navigation with environmental conditions for a Monte Carlo simulation with N=1000 in Figure 4.26. Due to the geometry of the encounter combined with the weather conditions, in some extreme cases, the vessels are unable to keep the desired track, resulting in the time-threshold being unable to be found. In this simulation, this occurred in approximately 2.4% of trials. From the histogram, 95% of all trials require less than 402 seconds to safely manoeuvre. This compares with the case

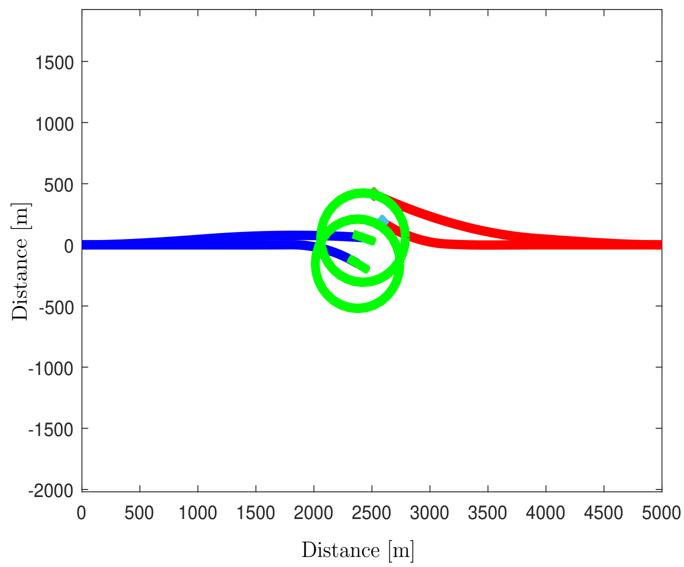

Figure 4.25: Compliant intruder head-on encounter scenarios for best and worst case scenarios in Monte Carlo simulation

without environmental conditions present, which results in a time-threshold of 228 seconds. See Figure 4.27 for the best and worst case scenarios from the Monte Carlo simulation.

4.4.4 Overtaking Intruder Case

For the overtaking case, another Monte Carlo simulation was performed with N=1000. See histogram of relative probabilities for the time-threshold required for safe navigation with environmental conditions for a Monte Carlo simulation with N=1000 in Figure 4.28. From the histogram, the all trials require less than 487 seconds to safely manoeuvre. Similar to the crossing case, there are failures resulting from the vessels unable to keep the desired course, this makes up approximately 7.5% of trials. This could potentially be remediated by changing the manoeuvre of the controlled vessel from the starboard to port side. This compares with the case without environmental

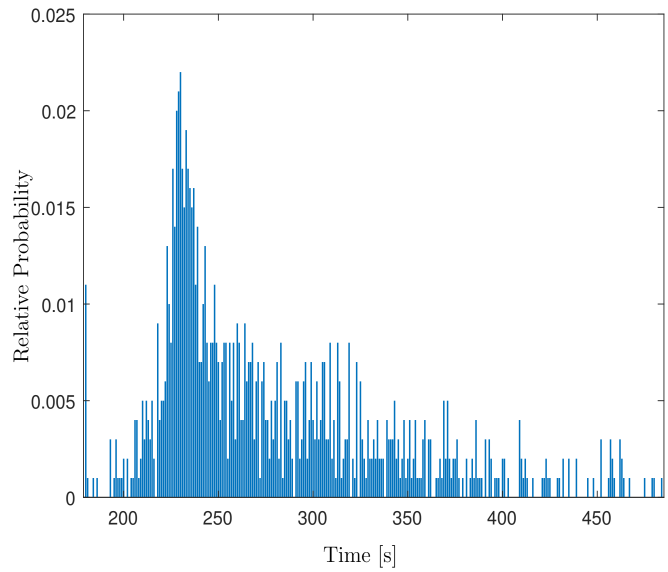

Figure 4.26: Crossing intruder encounter Monte Carlo simulation for environmental conditions with N=1000

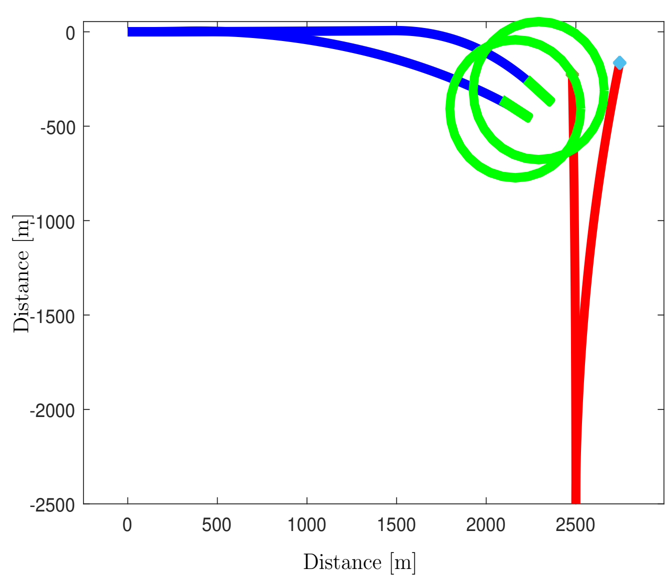

Figure 4.27: Crossing intruder encounter scenarios for best and worst case scenarios in Monte Carlo simulation

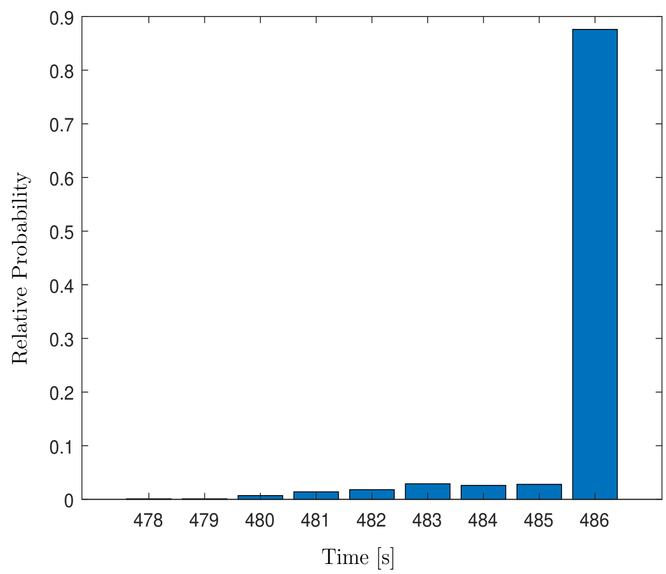

Figure 4.28: Overtaking encounter Monte Carlo simulation for environmental conditions with N=1000

conditions present, which results in a time-threshold of 487 seconds. See Figure 4.29 for the best and worst case scenarios from the Monte Carlo simulation.

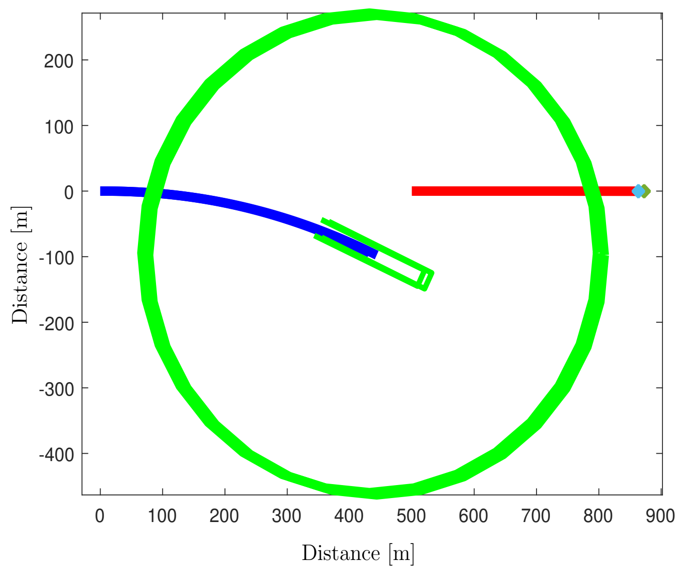

Figure 4.29: Overtaking encounter scenarios for best and worst case scenarios in Monte Carlo simulation

Chapter 5

Conclusions

From the results presented in this work, general rules that can be used for the establishment of self-separation time-thresholds can be inferred for both compliant and non-compliant intruders. These boundaries should take into effect the potential for adverse effects on the abilities of the vessel to navigate in certain environmental conditions, as demonstrated in the Monte Carlo analysis performed using environmental conditions observed near Newfoundland.

5.1 Contributions

Technical challenges encountered that were discussed in chapter 1 have been resolved throughout the project as follows:

1. Developing an accurate vessel model for the simulation - Using force modelling with physical data obtained from the NRC, an accurate vessel model has been developed

2. Developing an algorithm to determine the time required to safely manoeuvre - The developed algorithm runs an encounter scenario with an initial guess for time before closest point of approach to initiate a manoeuvre. When the time is reached, the controlled vessel begins to turn. If the predefined safety boundary is violated, the initial guess is incremented and the simulation starts over. When an encounter is run in which the boundary is not violated, this time threshold value is determined to be the minimum time required to manoeuvre for the vessel.

3. Accurately modelling the effects of the wind and surface currents on the vessel - The wind and surface current distributions were modelled using historic extremes data for St. John's and the forces applied as a result were modelled using a transverse strip method to apply moments to the vessel in addition to the forces.

4. Tuning the path following and surge controllers to precisely control the vessel during both calm water and non-calm water situations - Each of these controllers involve a PID loop being checked at the same frequency the position and speed the vessel are updated. The surge controller uses the error between the current speed of the vessel and the desired speed to increase or decrease the thrust force provided by the propeller. The path following controller calculates the distance to the nearest point on the discretized path and provides an input to the rudder to make sure that it is travelling towards this point. The control approach used was not novel work; existing control approaches were used and applied to the modelled vessel.

5.2 Publications

J. D. Mayo, K. Murrant, and S. O'Young, "Preliminary Definition of Detection and Reaction Boundaries for Autonomous Marine Traffic," in 2020 IEEE/OES Autonomous Underwater Vehicles Symposium (AUV), pp. 1-5, Sept. 2020. ISSN:2377-6536.

The goal of this project is to outline a preliminary approach to quantitatively define surveillance, declaration, and operating boundaries for autonomous marine traffic. This will be accomplished through an adaptation of Detect and Avoid Alerting Logic for Unmanned Aircraft (DAIDALUS) to the marine environment. Using the manoeuvring characteristics of a known vessel to manoeuvre, encounter geometries are analyzed using separation boundaries for safe operation and remedial action is suggested when a violation is expected to occur. Within this paper's scope, a formal definition of an autonomous vessel's alerting behaviour for various potential collision geometries is provided and applied to the development of collision avoidance scenarios. This definition, combined with the application in DAIDALUS, will provide the framework for defining the regulatory boundaries. Preliminary results are analyzed to inform regulatory development, refine the control approach to improve the safe, reliable operation of autonomous marine vessels and to investigate the feasibility of the selected method. [21]

J. D. Mayo, K. Murrant, and S. O'Young, "Time-based Collision Avoidance Thresholds for Autonomous Surface Vessels," in 2021 IEEE OCEANS, pp. 1-6, Oct. 2021.

The purpose of this project is to provide meaningful results to the establishment of reaction boundaries for the implementation of autonomous surface vessels

(ASVs). This will be accomplished by the completion of accurate modelling of a test vessel, which will be used for simulated collision avoidance trials in order to determine the minimum time required to avoid an intruder. The model of the test vessel will be developed using a Horizontal Motion model encompassing the surge, sway and yaw dynamics of the vessel. The method to be used will provide a suggested boundary based on the time to closest point of approach with the oncoming obstacle for any approach angle, in compliance with the International Regulations for Preventing Collisions at Sea 1972 (COLREGs) by the International Maritime Organization (IMO). [26]

5.3 Recommendations and Future Work

It is recommended that for the given test vessel, it adhere to the time-thresholds outlined in this work, with an additional safety factor in order to ensure sufficient reaction time. Additionally, in inclement weather that may impact the vessel's ability to manoeuvre, the vessel should change its operating point in order to allow for more time to manoeuvre and more closely adhere to the desired path.

According to the study, in a head-on encounter case, 179 seconds are required for a non-compliant intruder and 130 seconds are required for a compliant intruder when the controlled vessel is travelling at 10 knots. When converting this to distance, it would be approximately 920 metres for the non-compliant case and 670 metres for the compliant case. This would be the minimum required sensing capabilities for the algorithm to be implemented.

Potential future work for the project could include the application to other test vessels, in an effort to generalize the time-threshold results for vessels based on the classification of vessel, including environmental effect modelling for waves, determining the sensor capabilities required for the physical implementation of the self-separation algorithm, potential for implementation of an analytical solution with a prototype verification system with a test vessel and the physical testing itself using NRC facilities and/or a vessel in the open ocean.

By applying the simulation to other test vessels, the effects of changing the vessel can be observed to determine how great of an effect this would have on the time-thresholds required for safe navigation by both similar vessels and different vessel classes. These results could allow for the generalization of the time-threshold to apply to any potential vessel based on the size and ability to manoeuvre.

While waves would have little impact on a large vessel such as the one used for these simulations, future work may include wave force modelling to account for this additional impact. Also, if the simulation is completed for a smaller vessel, this would likely have a higher impact on the results of a Monte Carlo simulation.

Determining the sensor requirements for the physical implementation of the algorithm would allow for real-world testing. The sensors required would have to allow for the detection of oncoming intruders and obstacles far enough away that the controlled vessel is able to satisfy the time-threshold required to manoeuvre, along with sensors to allow for the surge and path following controllers to function properly.

A continuation of this project for the PhD will involve developing a collision avoidance system using a prototype verification system based on sequent calculus in order to ensure there are no errors in the functionality. The analytical verification is important to ensure that the safety critical system is functioning properly.

Lastly, physical testing would confirm the validity of the vessel model used for the simulation and provide insight into any deviations from the expected behaviour of the algorithm from the simulations that may need to be accounted for.

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